Spatial Variability of Coalbed Natural Gas Produced Water Quality, Powder River Basin, Wyoming: Implications for Future Development

Scott A. Quillinan and Carol D. Frost

WYOMING STATE GEOLOGICAL SURVEY
Thomas A. Drean, Director and State Geologist

Director and State Geologist Thomas A. Drean

Edited by:
Mary Kate McCarney

Design & Layout by:
Chamois L. Andersen

East of Wyoming Highway 59, view from Logan Hill toward the northeast, Powder River Basin, Campbell County, Wyoming. Photo by David Lucke.

Spatial Variability of Coalbed Natural Gas Produced Water Quality, Powder River Basin, Wyoming: Implications for Future Development

Wyoming State Geological Survey (WSGS) Report of Investigations No. 64, 2012
ISBN 978-1-884589-59-1

Spatial Variability of Coalbed Natural Gas Produced Water Quality, Powder River Basin, Wyoming: Implications for Future Development

Wyoming State Geological Survey
Report of Investigations No. 64
2012

Scott A. Quillinan[1,2,3] and Carol D. Frost[3]

[1]Wyoming State Geological Survey, Laramie, Wyoming 82071
[2]Carbon Management Institute, University of Wyoming, Laramie, Wyoming 82071
[3]Department of Geology and Geophysics, University of Wyoming, Laramie, Wyoming 82071

Table of Contents

List of Figures

List of Tables

Abstract

Coalbed natural gas (CBNG) production is associated with large volumes of produced water. To date, approximately 12 percent (3.7 TCF) of the CBNG resource in Wyoming's Powder River Basin (PRB) has been produced. Significant gas resources remain but will require the continued production of large volumes of water.

In this report, we classify the approximately 30,000 producing, shut-in, permitted, and permanently abandoned CBNG wells by coal zone. Focusing on the five largest CBNG producing coal zones, we calculate water to gas ratios, define "core producing areas," and identify potential areas of future development of these coal zones. In addition, we use water quality data for 337 previously published produced water samples from specific coal zones to map the spatial variability of total dissolved solids and sodium adsorption ratios within these core-producing areas and to identify potential beneficial uses.

Results from this study show that groundwater quality becomes more saline and sodic with increasing residence time in the coal bed aquifers. CBNG produced water quality correlates more strongly to geographic location than to coal zone. With the information presented in this study, it is possible to estimate the produced water quality of future development within producing coal zones. The available water quality data suggest that most of the CBNG produced water in the PRB can be used to water livestock and, with careful management practices, irrigate salt-tolerant plants.

Introduction

Coalbed natural gas (CBNG) is associated with larger volumes of produced water than is recovered during traditional oil and gas production (Veil et al., 2004). Throughout the last century, produced water in Wyoming was mainly associated with oil production. The growth in CBNG production in Wyoming since 2000 is accompanied by a dramatic increase in the volume of produced water (Figure 1).

The Powder River Basin (PRB) hosts Wyoming's largest natural gas producing area, accounting for 21 percent of the state's total natural gas production (WOGCC, 2010). During 2011, CBNG wells in the PRB produced 478 billion cubic feet (BCF) of gas and 489 million barrels (MmBbls) of produced water (Figure 2). This equates to an average of 1.0 barrel (42 gallons) of water produced for each thousand cubic foot (MCF) of natural gas, although for individual wells the water to gas ratio is highly variable. National natural gas reserves have significantly increased in recent years, which have depressed the market price of natural gas. As a result, CBNG production in the PRB has been in decline since 2009 (Figure 2). Through 2011, over 4 TCF of gas has been produced, which represents roughly 12 percent of the total estimated natural gas resource of the PRB (WSGS, 2010).

CBNG production benefits from a large network of wells that work collectively to lower the hydrostatic pressure, which enables gas to desorb and rise to the surface. As more wells are drilled in a given area, sufficiently low hydrostatic pressure can be attained with less water production per well. Currently well networks are focused in the central and northern part of the PRB (Figure 3). Recovering the remaining gas resource will require expanding well networks into new areas which will require the production of additional volumes of water. In order to minimize the cost of managing produced water, it is important to focus natural gas recovery from coal seams that produce relatively low water to gas ratios and where water is of sufficiently good quality that it can be put to beneficial use.

CBNG produced water in the PRB is strongly sodium-bicarbonate type with salinities that

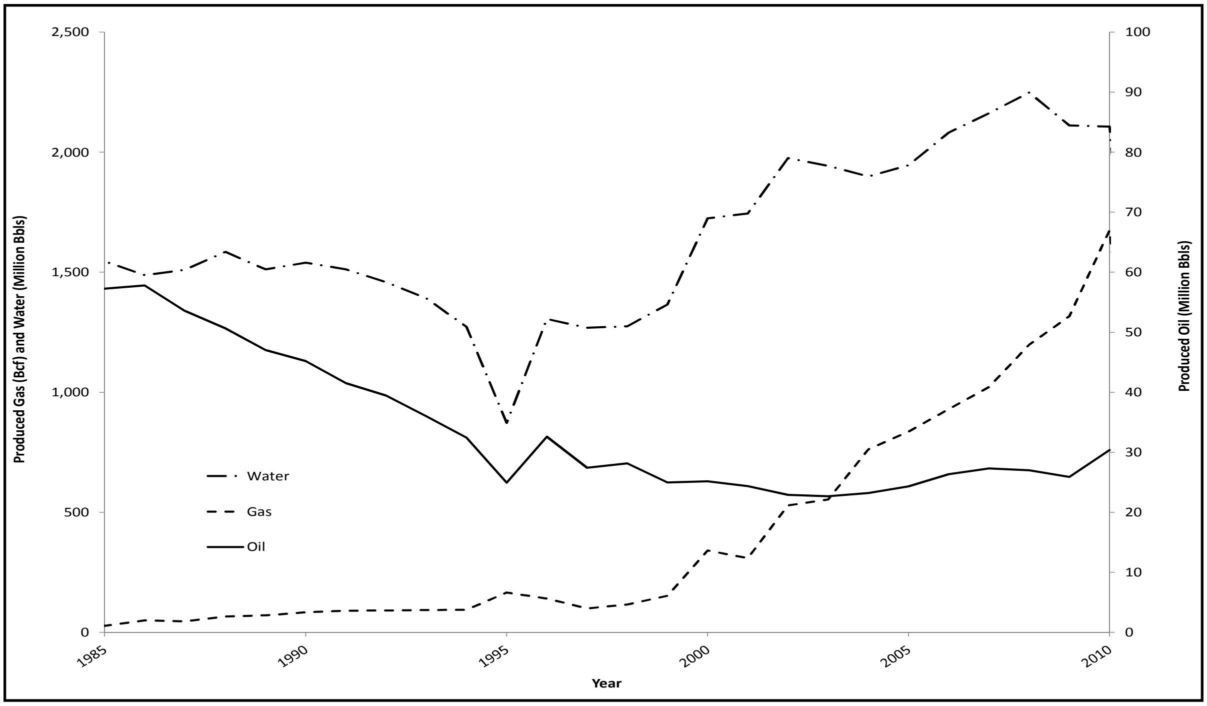

Figure 1. Oil, water, and gas production from the 50 largest water producing fields in Wyoming. Data from Wyoming Oil and Gas Conservation website (2010).

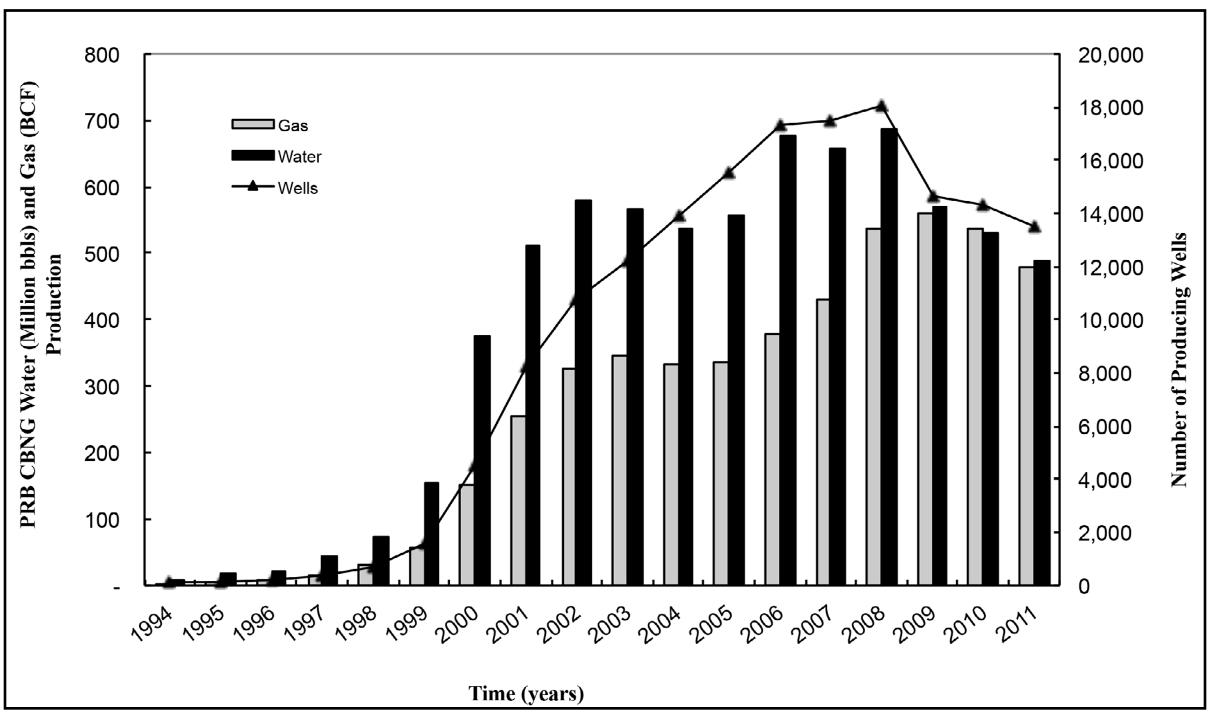

Figure 2. Development of coalbed natural gas in the Powder River Basin from 1994-2011. The number of wells and the amount of gas and produced water increased dramatically starting around 2000 and peaking in 2008, and since then has been in steady decline. Data from the Wyoming Oil and Gas Conservation website (2012).

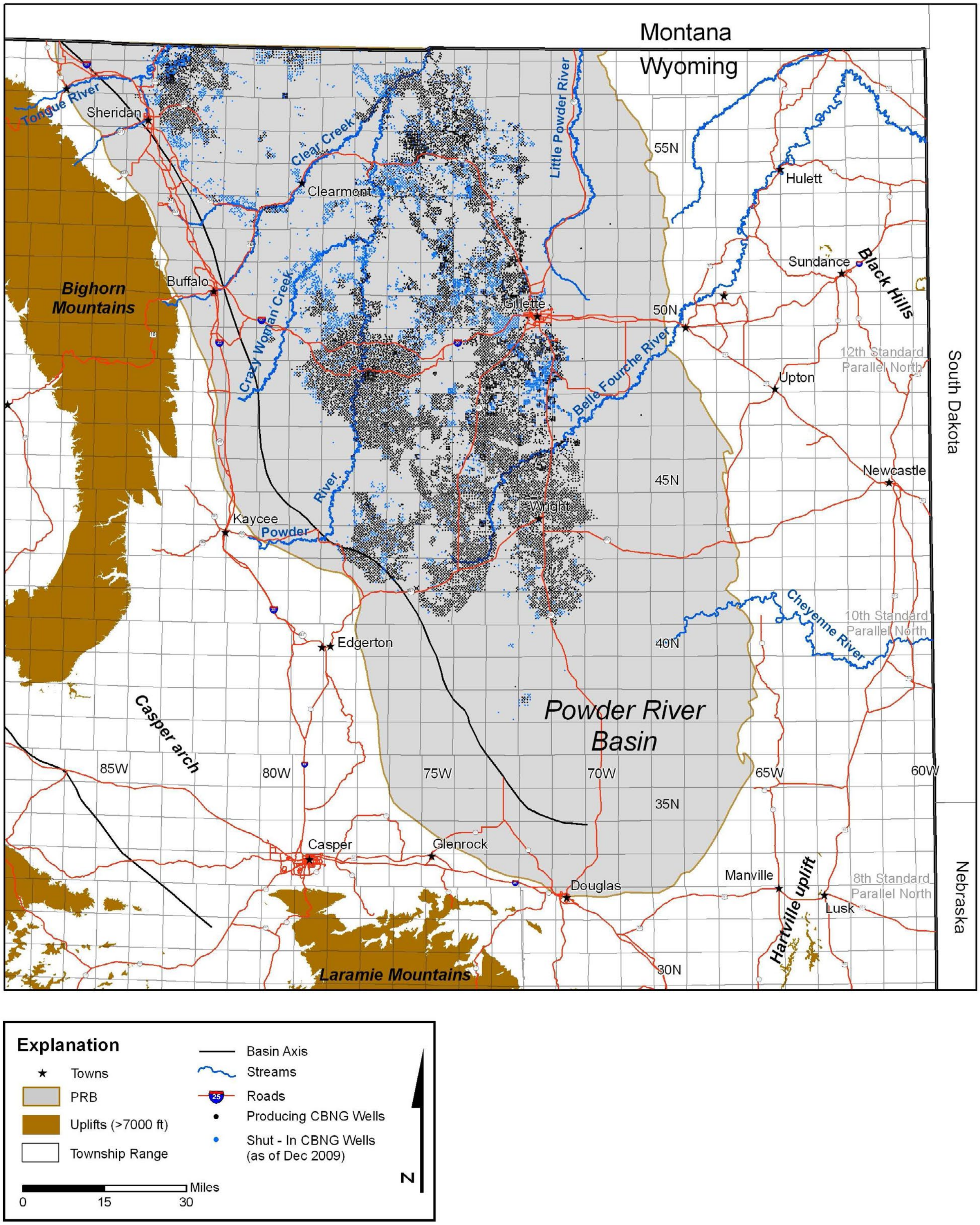

Figure 3. Location of CBNG wells in the Powder River Basin, including producing wells (black dots) and shut-in wells (blue dots). Data from Wyoming Oil and Gas Conservation website (2010) and Quillinan et al. (2010).

range from 500-5,000 milligrams per liter (mg/L; Rice et al., 2000; Bartos and Ogle, 2002; Pearson, 2002; Frost et al., 2002; Campbell et al., 2008; and Quillinan, 2011a). Sodicity, measured by sodium adsorption ratio (SAR), ranges from 5 to 60 (Campbell et al., 2008). For comparison, surface waters of the Powder River have median TDS concentrations of 1,500 mg/L and SAR of 6 (Brinck et al., 2008). The salinity and sodicity of all coal zones varies spatially, with more dilute, lower SAR water produced in the southeast part of the basin near the main recharge areas. Salinity and sodicity tend to increase to the west and north along flow path, with the highest values in the central part of the basin beneath the Powder River (Rice et al., 2000; Bartos and Ogle, 2002; and Campbell et al., 2008). However, these trends were identified primarily on water quality data from the Wyodak Rider and Upper Wyodak coal zones, and only Campbell et al. (2008) attempted to examine the data by coal zone. Analysis of a more comprehensive data set is required to predict the quality of water that in the future may be produced from specific coal zones in particular geographic locations.

The purpose of this report is to describe the quantity and quality of produced water derived from five coal zones in the PRB. First, we describe the geographic location of CBNG production from each of the five, main producing coal zones. We determine the volumes of cumulative produced water and gas from these five coal zones and calculate the water to gas ratio for each. We examine new and published water quality data for produced water from each coal zone and plot spatial variations in salinity and sodicity. The water quality of produced water from each coal zone is then evaluated to determine its potential beneficial uses, be it for drinking water, irrigation, livestock, or other uses. This information is then used to identify geographic areas with remaining development potential for each coal zone and to predict the water quality and water to gas ratios anticipated in these expanded areas.

Coal Geology of the Powder River Basin

The coals in the PRB are found within the Tongue River member of the Paleocene Fort Union Formation and in the Eocene Wasatch Formation (Love and Christiansen, 1985). Jones (2008; pers. comm., 2010) has identified 10 distinct coal zones that contain 26 coal beds within the Tongue River member and the overlying Wasatch Formation (Figure 4). The Tongue River Member hosts the thick, laterally continuous coal beds that are mined on the eastern side of the basin. This report focuses on the Paleocene coal zones in the PRB from which most CBNG is produced, including the Wyodak Rider, Upper Wyodak, Lower Wyodak, Cook, and Wall coal zones. The average and maximum thicknesses of the coal beds within these coal zones and their areal extent are presented in Table 1.

Wyodak Rider Coal Zone

The Wyodak Rider coal zone is the youngest of the five major CBNG producing coal zones. It consists of three main coal beds, from youngest to oldest, the Smith Rider, Smith/Big George, and Lower Smith. These three coals merge in the center of the basin where they are referred to as the Big George coal bed. CBNG is produced from this zone near the basin axis where it is up to 2,750 feet deep (Jones, 2008). The coals in the Wyodak Rider coal zone have limited outcrop north and west of Sheridan, but for the most part these coals split and pinch out in the subsurface (Jones, 2008).

Upper Wyodak Coal Zone

The Upper Wyodak coal zone is stratigraphically below the Wyodak Rider coal zone and contains three main coal beds, from youngest to oldest, the Anderson Rider, Wyodak, and Lower Anderson (Jones, 2008). This coal zone is the most extensive of the five CBNG-producing

<table>
<tr><th>Formation</th><th>Coal zone</th><th colspan="2">Coal bed</th></tr>
<tr><td rowspan="3">Wasatch</td><td>Upper Wasatch</td><td colspan="2">Ulm
Lake DeSmet
U Cross</td></tr>
<tr><td>Felix</td><td colspan="2">Felix Rider
Upper Felix
Felix</td></tr>
<tr><td>Lower Wasatch</td><td colspan="2">Arvada
Unnamed</td></tr>
<tr><td rowspan="10">Fort Union
Tongue River
member</td><td>Roland</td><td colspan="2">Upper Roland
Roland of Baker
Roland of Taft</td></tr>
<tr><td>Wyodak Rider</td><td colspan="2">Smith Rider
Smith/Big George
Lower Smith</td></tr>
<tr><td rowspan="2">Upper Wyodak</td><td>East</td><td>West</td></tr>
<tr><td>Anderson Rider (Anderson)
Anderson (Wyodak)
Lower Anderson</td><td>Dietz 1
Dietz 2</td></tr>
<tr><td rowspan="2">Lower Wyodak</td><td>East</td><td>West</td></tr>
<tr><td>Canyon Rider
Canyon</td><td>Dietz 3</td></tr>
<tr><td>Cook</td><td colspan="2">Cook (Werner)
Lower Cook (Gates)</td></tr>
<tr><td>Wall</td><td colspan="2">Wall
Lower Wall
Pawnee</td></tr>
<tr><td>Basal Tongue River</td><td colspan="2">Moyer</td></tr>
</table>

Figure 4. Coal stratigraphy of the Powder River Basin, Wyoming, from Jones (2008; pers. comm. 2010).

coal zones, and represents the most continuous hydrogeologic unit of the Tongue River member (Table 1; Bartos and Ogle, 2002). Outcrops of the Upper Wyodak coal zone can be traced along the entire eastern margin of the basin where the Tongue River Formation is exposed. The Upper Wyodak coal beds split and coalesce in various regions. For example, the Upper Wyodak coals coalesce with the Canyon coal of the Lower Wyodak coal zone on the eastern side of the basin, where they are mined extensively. In the northwestern side of the basin, the Upper Wyodak coal zone consists of the Dietz 1 and 2 coal beds. The Upper Wyodak coals were the first coals targeted for CBNG development in the PRB (WOGCC, 2010).

Lower Wyodak Coal Zone

The Lower Wyodak coal zone consists of two main beds, the Canyon Rider and the basal Canyon coal. The Lower Wyodak coal zone is present in the eastern and northern half of the PRB. The Canyon Rider is found only in the northeast portion of the basin (Jones, 2008). In

Table 1. Average thickness, maximum thickness and areal extent of coal beds within the five main CBNG producing coal zones of the Powder River Basin from Jones (2008; pers. comm. 2010).

Coal zone	Coal bed	Avg. Thickness (ft.)	Max. Thickness (ft.)	Areal extent (thousand acres)
Wyodak Rider	Smith Rider	17	107	668
	Smith/Big George	38	216	1,791
	Lower Smith	18	100	1,703
Upper Wyodak	Anderson Rider (Anderson)	13	52	1,032
	Anderson (Wyodak)	47	208	3,789
	Lower Anderson	21	167	2,998
Lower Wyodak	Canyon Rider	10	38	335
	Canyon	25	205	1,689
Cook	Cook (Werner)	22	145	1,788
	Lower Cook (Gates)	9	38	638
Wall	Wall	19	139	1,862
	Lower Wall	11	58	3,177
	Pawnee	11	50	1,097

this study, where the Upper and Lower Wyodak coals merge, they are considered as part of the Upper Wyodak coal zone.

Cook Coal Zone

The Cook coal zone consists of two mappable coal beds, the Cook and Lower Cook. The Cook is the main CBNG target in this coal zone. The Lower Cook is much thinner and therefore not as favorable for CBNG production (Table 1). The Wyoming Oil and Gas Conservation Commission (WOGCC) refer to the Cook and Lower Cook beds as the Werner and the Gates, respectively. In some places, operators have interchanged the names, calling the upper coal the Gates and the lower coal the Werner.

Wall Coal Zone

The Wall coal zone is stratigraphically lowest of the main CBNG producing coal zones. It consists of three major horizons: the Wall, the Lower Wall, and the Pawnee (Jones, 2008). Most CBNG recovered from this coal zone comes from the Wall coal bed; although the two lower, beds also produce natural gas (WOGCC, 2010).

Methods

Geospatial Analysis

The CBNG well database used in this report originated from the Wyoming Oil and Gas Commission (WOGCC, 2010). Geospatial analysis was performed using ESRI ArcGIS software. Wells were sorted by the coal bed in which they were completed, and then grouped into coal zones using the nomenclature described by Jones (2008; pers. comm., 2010). The accuracy of these classifications depends on how accurately the producing interval was reported to the WOGCC. Due to the complexity of coal stratigraphy in the basin, coal names reported to the WOGCC by operators can be inconsistent. For this reason, we use coal zones to group individual coal beds within a particular sequence. The use of a coal zone simplifies the spatial analysis by grouping each sequence of related beds into a stratigraphic interval (Jones, 2008). We note that despite classifying into coal zones, inconsistencies within the WOGCC database still occur. We estimate that fewer than 5 percent of wells are inaccurately classified.

From this compilation, we identified and outlined the geographic area(s) where CBNG production is most concentrated within each coal zone. This area we term the "core producing area" (CPA); the extent of these areas is shown on Figure 5. We also determined the geographic extent of each coal zone where one or more coal beds has a thickness greater than 10 feet. Gray shading on Figures 7, 10, 13, 16, and 19 show these coal zone extents.

TDS and SAR for the CPAs were interpolated with an inverse distance-weighted algorithm using Environmental Systems Research Institute (ESRI) spatial analyst software. Contours were smoothed and quality-checked by hand. Depending on data density, outliers do occur in the contouring.

CBNG Water Quantity and Water to Gas Ratios

Data on gas and water production from PRB CBNG wells are also available in the Wyoming Oil and Gas Commission well database (WOGCC, 2010). Water to gas ratios were calculated for each of more than 30,500 wells using cumulative water and gas data reported to the Wyoming Oil and Gas Commission (Table 2). Several wells displayed within each CPA have multiple coal zone completions, and because it is not possible to determine the proportion of water and gas derived from each coal zone for these wells, water and gas production from multi-zone completed wells are not reflected in Table 2. For this reason, the total produced water and gas from each coal zone given in the table are underestimates. Wells with multiple completions are included in the "number of wells" column of Table 2 and are shown in Figure 5.

Table 2. Number of wells, gas and water production in the Powder River Basin. *Includes multi-zone completed wells. Only wells that have single coal zone completions were considered for water and gas production numbers in order to calculate water to gas ratios by coal zone. The number of wells reported for each coal zone includes both wells with single and multiple coal zone completions.

Coal zone	No. of wells	Water production (MmBbls)	Gas production (BCF)	Water: gas (Bbls/MCF)	Average TDS (mg/L)	Average SAR
Wyodak Rider	9396*	1,200	1,100	1.1	2660	17.6
Upper Wyodak	8586*	1,200	770	1.6	880	9.9
Lower Wyodak	2211*	330	174	1.9	1118	11.8
Cook	3795*	238	155	1.5	2121	20.6
Wall	6551*	495	130	3.8	1571	17.9

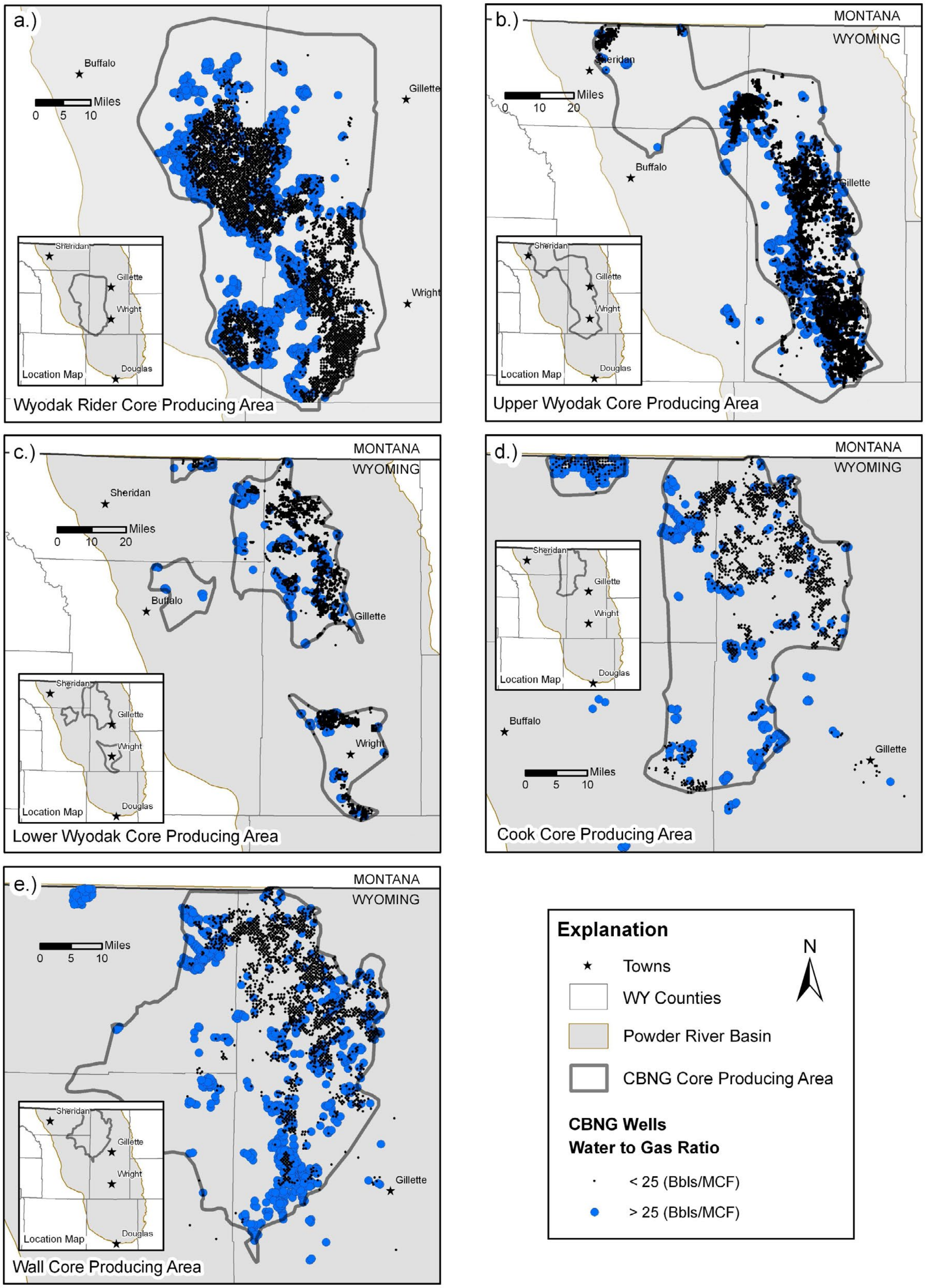

Figure 5. Core Producing Areas for five coal zones in the Powder River Basin: a) Wyodak Rider coal zone, b) Upper Wyodak coal zone, c) Lower Wyodak coal zone, d) Cook coal zone, e) Wall coal zone. For each coal zone, the wells completed within the coal zone are shown. Wells with water to gas ratio greater than 25 Bbls/MCF based on cumulative production are identified by blue dots; wells with lower water to gas ratios are indicated by black dots.

CBNG Water Quality

A total of 156 published water quality analyses were compiled from Pearson (2002), Frost et al. (2002), and Campbell et al. (2008). Our study includes an additional 170 unpublished water quality analyses from the Wyoming Department of Environmental Quality; these are available in Appendix A.

The analytical results, available in Appendix A, include two key parameters that are calculated from the water quality data: total dissolved solids (TDS), a measure of salinity, and sodium adsorption ratio (SAR)[1], a measure of sodicity. These parameters are of interest particularly if the produced water may be used for irrigation. Different plants have varying tolerance for salinity but in general, high salinity can affect germination and the emergence and growth of seedling plants. SAR is another important measure of the suitability of water for irrigation. Irrigation with waters that are high in sodium relative to calcium and magnesium can degrade soil quality. Over time, the application of high SAR water to clay-rich soils will disperse clay particles causing swelling soils and reduced soil porosity, water infiltration, and root penetration (Hanson et al., 1999). The potential impacts of high SAR are less severe when the water is of higher salinity because a higher electrolyte concentration in soil solution reduces the effect of sodium-induced swelling of clays and associated changes in soil structure (Hoffman et al., 1990).

[1] *Sodium adsorption ratio (SAR) is defined as follows:*

$$SAR = \frac{Na^{+}}{\sqrt{\frac{Ca^{2+} + Mg^{2+}}{2}}}$$

where ion concentrations are in milliequivalents per liter (Stumm and Morgan, 1996).

Table 3. Percentage of undeveloped area outside of the current coal zone core producing area. Note that large areas remain in all five-coal zones to be developed outside of the current CPA, particularly in the stratigraphically lower coals.

Coal Zone	Total Coal Zone Extent (mi^2)	Total Coal Zone Extent > 10 ft (mi^2)	Core Production Area (mi^2)	Coal Zone Extent > 10 ft outside of CPA (mi^2)	Percentage of >10 ft outside of CPA
Wyodak Rider	5,409	2,940	2,215	1,047	36%
Upper Wyodak	6,504	4,987	3,547	2,117	42%
Lower Wyodak	5,737	2,423	1,889	1,238	51%
Cook	5,995	3,545	1,244	2,456	69%
Wall	6,327	4,335	1,692	2,804	65%

Results

Identification of "Core Producing Areas" for Each Coal Zone

The geographic extent of the five coal zones examined is approximately 6,000 mi^2 (Table 3). However, the area in which coal thickness is at least 10 feet is smaller, and varies from 2,400 mi^2 for the Lower Wyodak coal zone to nearly 5,000 mi^2 for the Upper Wyodak coal zone. Natural gas production lies mainly within the areas where coals are more than 10 feet thick, but the production areas are smaller than the total area underlain by coals greater than 10 feet thick.

Although overlapping in part, the core producing areas (CPA) for the five coal zones occupy different parts of the PRB (Figure 5). Production from the Wyodak Rider coal zone is focused in the central portion of the basin, and CBNG production from the stratigraphically lower coal zones (Upper and Lower Wyodak) is displaced towards the eastern margin of the basin nearer the coal outcrop. The Cook and Wall coal zone production areas are near the Wyoming/Montana state line, where these stratigraphically lowest coals are present at shallower depths.

Water Quantity and Water to Gas Ratios

The amount of water produced from each coal zone is variable, ranging from 238 million barrels (MmBbls) for the Cook coal zone, to 1,200 MmBbls for the Upper Wyodak coal zone (Table 2). These data, combined with gas production data, allow us to determine the average water to gas ratio by coal seam. The most favorable gas to water production— that is, the lowest water to gas ratio— is associated with the Wyodak Rider coal zone, where 1.1 Bbls of water are produced for every thousand cubic feet (MCF) of gas. The Wall coal zone has highest water to gas ratio: 3.8 Bbls water for each MCF of gas (Table 2).

Water to gas ratios vary spatially and temporally in the PRB. Water production generally declines over the lifetime of a well, and gas production may not commence immediately, leading water to gas ratios to vary with time. Spatial variations reflect in part the pattern of CBNG production, which typically expands outward from a cluster of initial wells. Wells drilled farther from the CPAs tend to have higher water to gas ratios, at least initially (Figure 5). However, some areas and coal zones produce more gas or water than others, while some never produce commercial quantities of gas. Figures 7, 10, 13, 16, and 19 identify areas within the CPAs of each coal zone that produce gas more effectively than others do. Areas in which there are many shut-in or abandoned wells may identify areas where it is not economical to operate for reasons that could include poor gas production, high water production, and/or poor water quality.

Water Quality

The geochemistry of produced water from all coal zones is strongly sodium bicarbonate type (n=337; Figure 6). Sulfate is detected in some

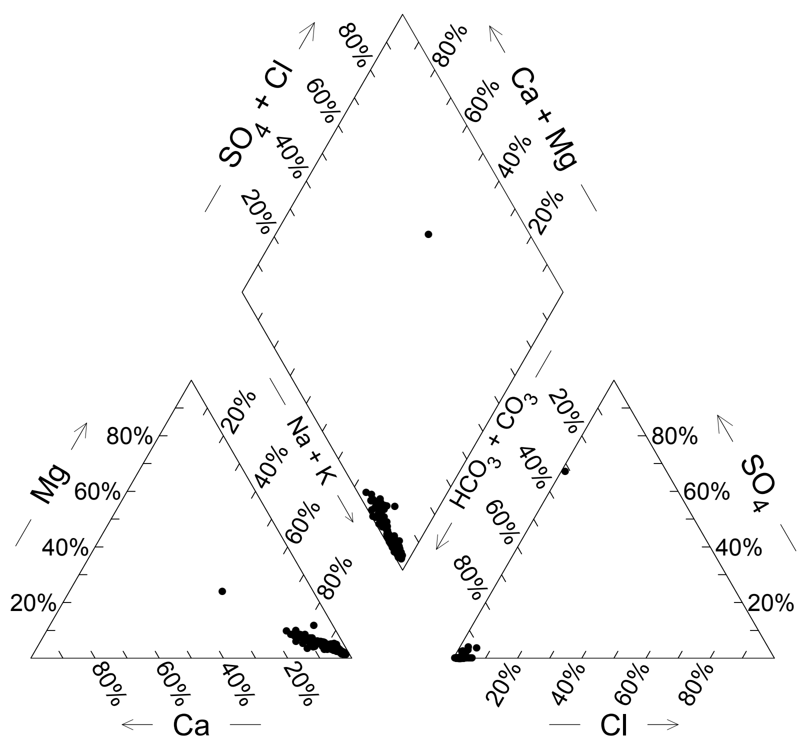

Figure 6. Trilinear plot showing chemical composition of CBNG produced water. With one exception, all samples are strongly sodium bicarbonate type.

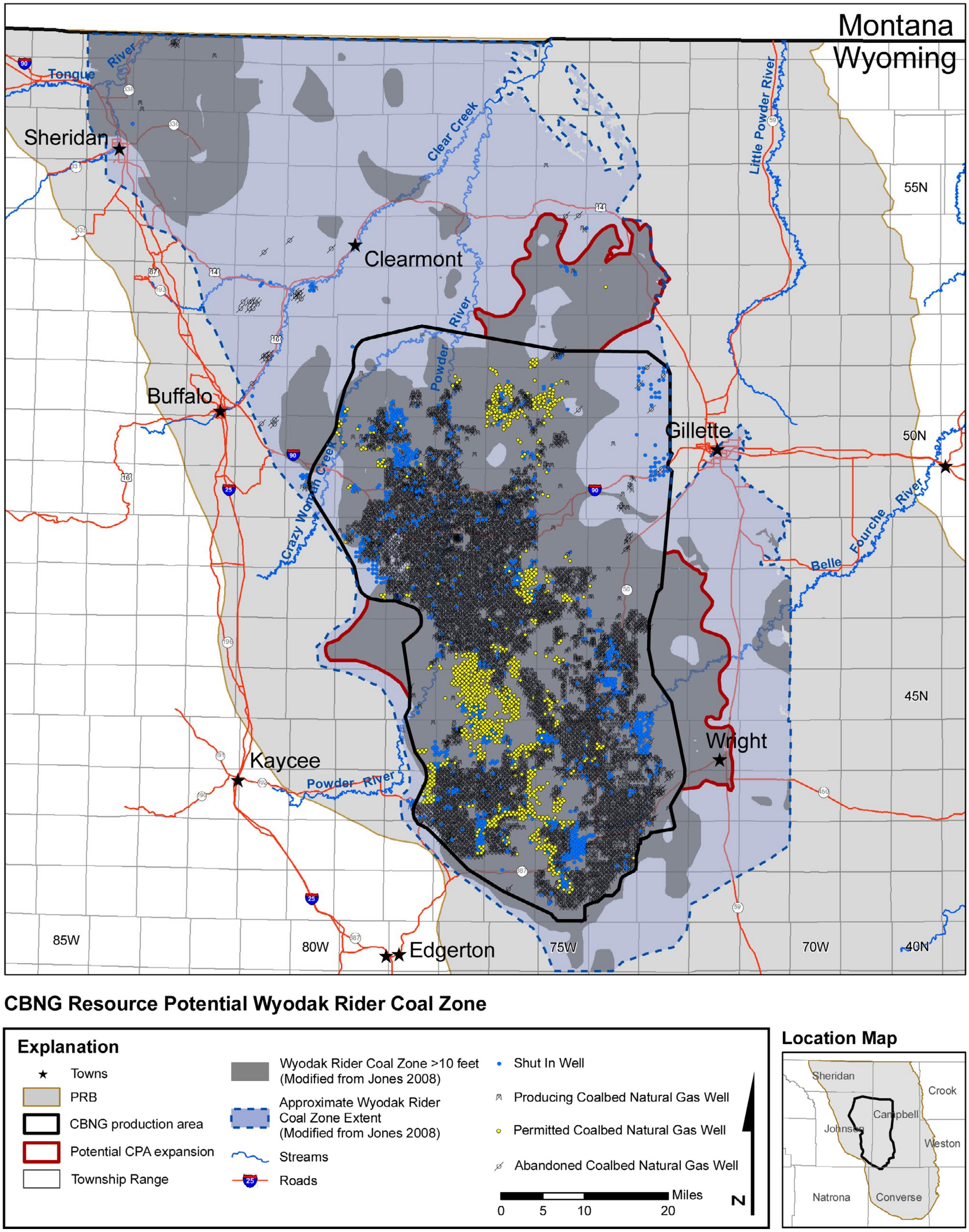

Figure 7. CBNG Resource Potential of the Wyodak Rider coal zone, showing present core producing area (outlined in thick black line), producing, shut in, abandoned and permitted CBNG wells, and areas for possible future CBNG development of the Wyodak Rider coal zone (outlined in thick red line). Coal thicknesses and coal zone extent is updated from Jones (2008).

shallow wells near recharge that generally also have low TDS.

The highest TDS (4,467 mg/L) was measured in the Wyodak Rider coal zone in the basin center whereas the lowest TDS (362 mg/L) was measured in the Upper Wyodak coal zone proximal to outcrop. The highest SAR value was 108, from a sample of produced water from the Upper Wyodak coal zone near the Wyoming-Montana state line. The lowest SAR values of 3 were obtained from water produced from the Upper Wyodak at the southern edge of the CPA. Current Wyoming Department of Environmental Quality standards for irrigation wells requires a TDS of 2,000 mg/L or less and a SAR 8 or less.

Detailed Results by Coal Zone

Wyodak Rider

The Wyodak Rider core producing area was determined from the locations of 9,396 wells producing from the Wyodak Rider coal zone (Figure 5a). The Wyodak Rider CPA was defined to encompass all but 49 of these wells. Most of these 49 wells are located across an area north of the CPA in locations where the coals are thinner than 10 feet. Many other wells in this area have been abandoned. The remaining wells are located north of Sheridan near the Montana border, and tend to have high water to gas ratios. The Wyodak Rider core producing area is 2,216 mi^2 and is located in parts of Campbell, Johnson, and Converse counties.

Nearly one third of the gas produced in the PRB has come from the Wyodak Rider coal zone (1,100 BCF; Table 2).. The total water produced from the Wyodak Rider coal zone is 1,200 MmBbls, for a cumulative water-to-gas ratio of 1.08 Bbls of water per MCF of gas (Table 2). Water to gas ratios are highest on the outer edge of the producing clusters and are higher on the western side of the CPA (Figure 5a).Water quality data for the produced water from the Wyodak Rider coal zone is based on data from 98 samples (Figure 6; Appendix A). Total dissolved solids range from 571 mg/L for a sample located in the southeast of the CPA to 4,467 mg/L for a sample collected in the northwestern part of the CPA. The average TDS for produced water from the Wyodak Rider coal zone is 1,768 mg/L. TDS generally increases along the approximate groundwater flow path from the southeast to the northwest of the CPA (Figure 8). SAR for the Wyodak Rider CPA ranges from 5 in the southeastern part of the CPA to 59 in the north, with an average value of 11.8. The highest SAR values coincide with the area where the Big George coal is thickest. As was the case for TDS, SAR values generally increase from the southeast to the northwest, parallel with the direction of groundwater flow (Figure 9).

Upper Wyodak

The Upper Wyodak CPA was defined based on the location of 8,586 wells. All but 1 percent (71) of these wells lie inside of the CPA. The Upper Wyodak CPA lies mainly in Campbell County, but also occupies portions of Sheridan, Johnson, and Converse counties (Figure 10). We have included in the Upper Wyodak CPA areas where Upper Wyodak coals have merged with the Canyon coal bed of the Lower Wyodak coal zone.

The Upper Wyodak coal zone has produced 770 BCF of gas and 1.2 MmBbls of water. The cumulative water to gas ratio for the Upper Wyodak coal zone is 1.6 Bbls of water per MCF of gas (Table 2). Production in this coal zone started in the east near coal outcrop and subsequently moved westward. Shallow wells in the east where production started currently produce little to no water. A number of the older wells no longer produce gas and have been temporarily or permanently abandoned (Figure 10).

The chemical composition of the produced water in the Upper Wyodak Coal zone is based

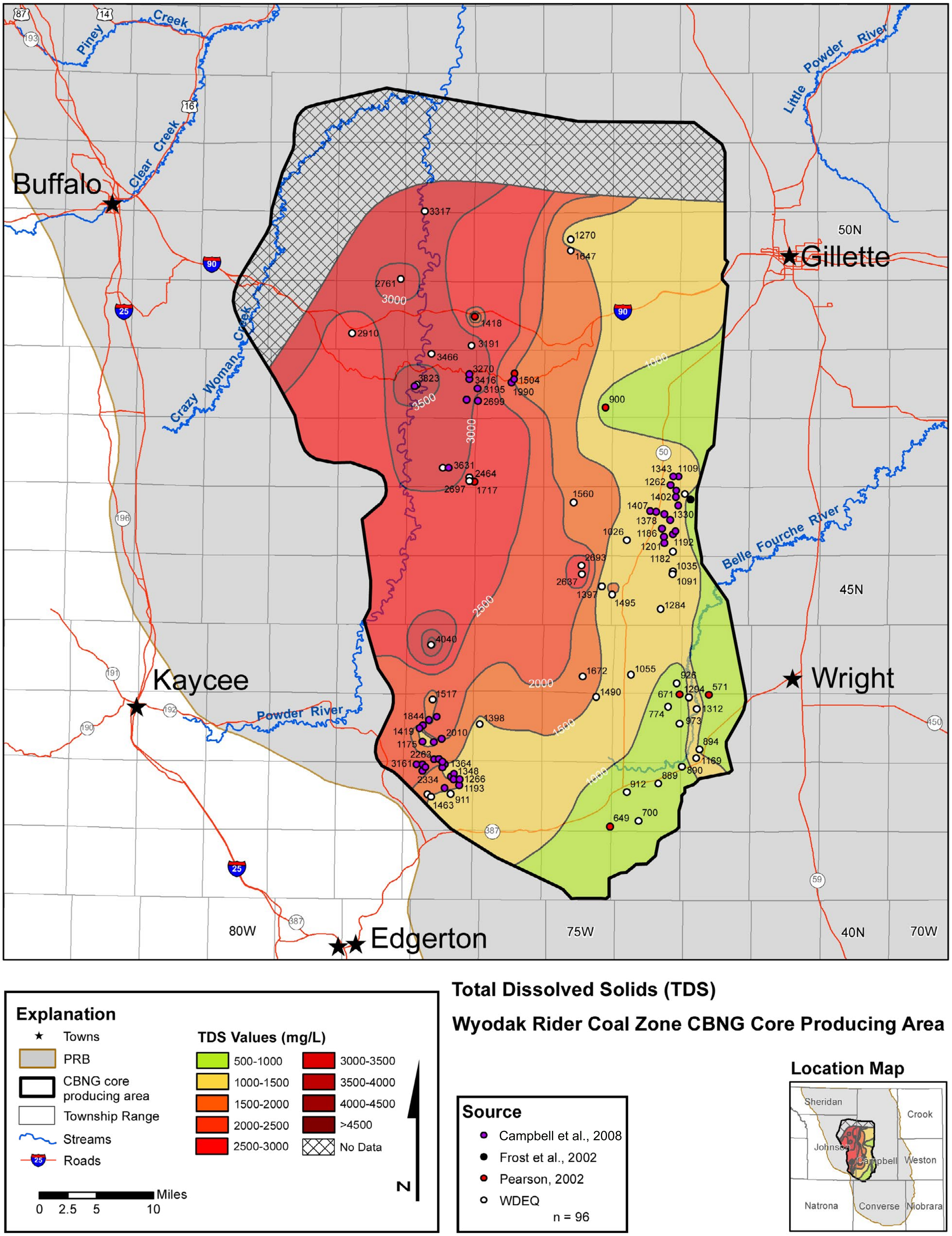

Figure 8. Spatial distribution of TDS for produced water from the Wyodak Rider coal zone within the core producing area. Note increase in TDS from southeast to northwest.

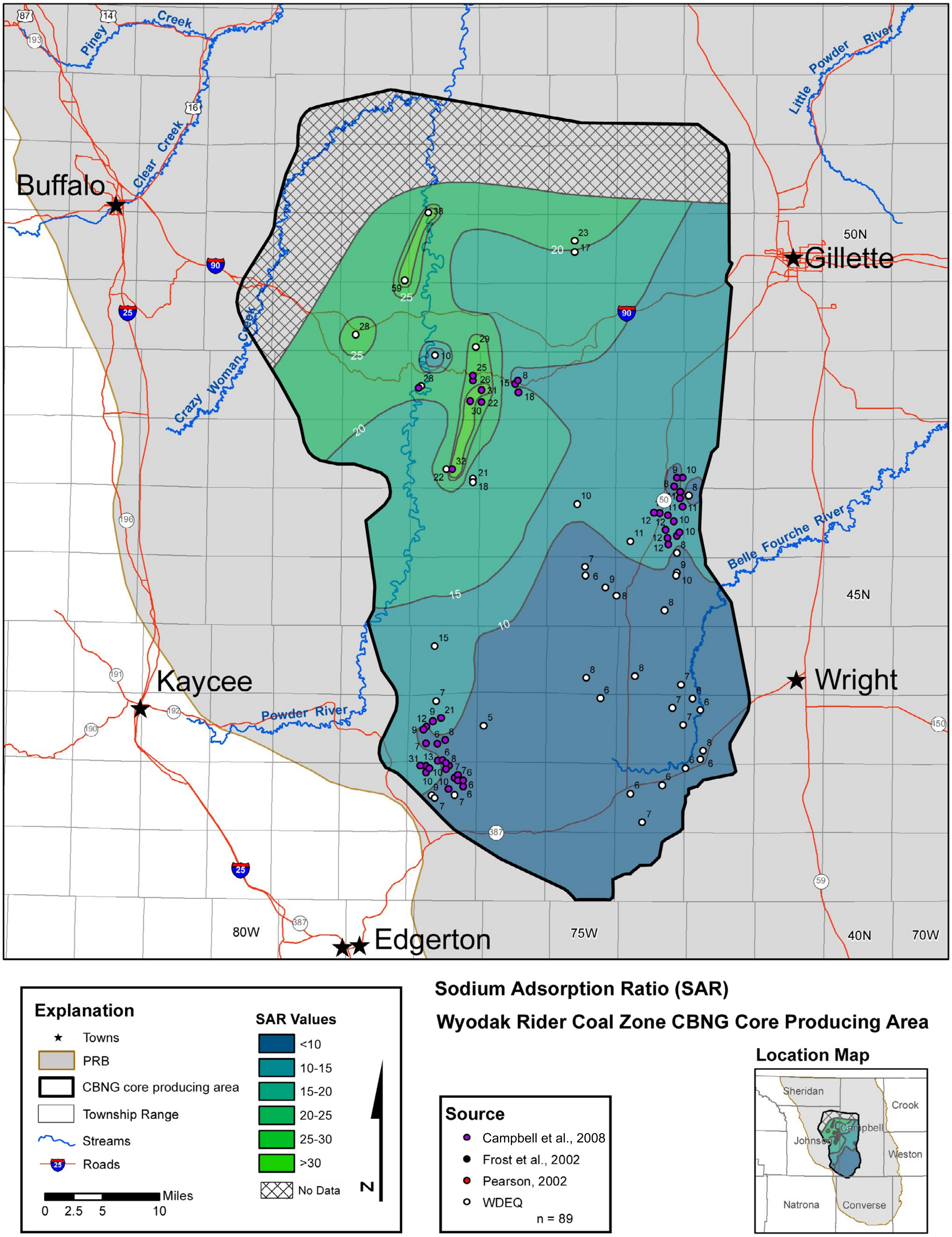

Figure 9. Spatial distribution of SAR for produced water from the Wyodak Rider coal zone within the core producing area. Note increase in SAR from southeast to northwest.

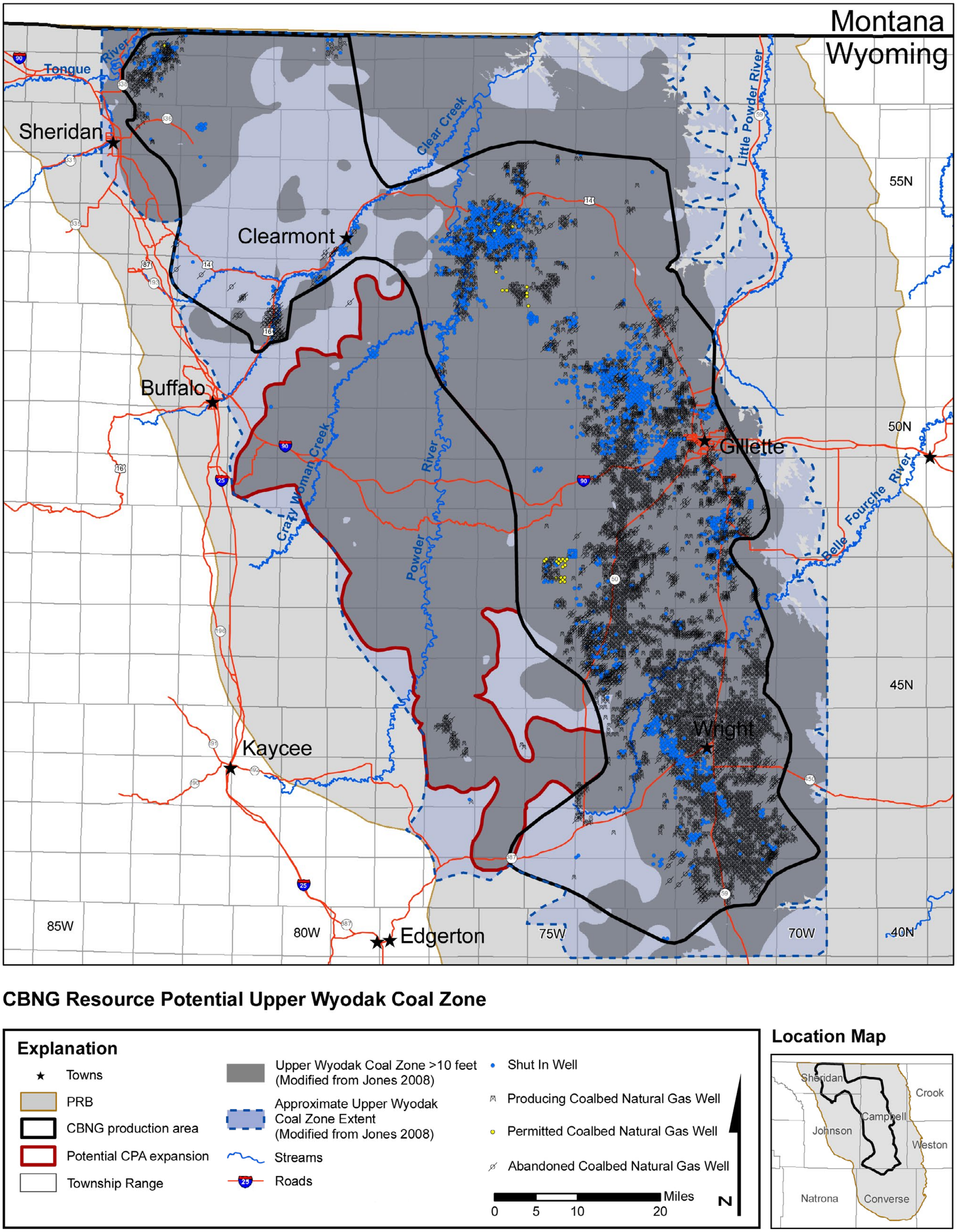

Figure 10. CBNG Resource Potential of the Upper Wyodak coal zone, showing present core producing area (outlined in thick black line), producing, shut in, abandoned and permitted CBNG wells, and areas for possible future CBNG development of the Upper Wyodak coal zone (outlined in thick red line). Coal thicknesses and coal zone extent is updated from Jones (2008).

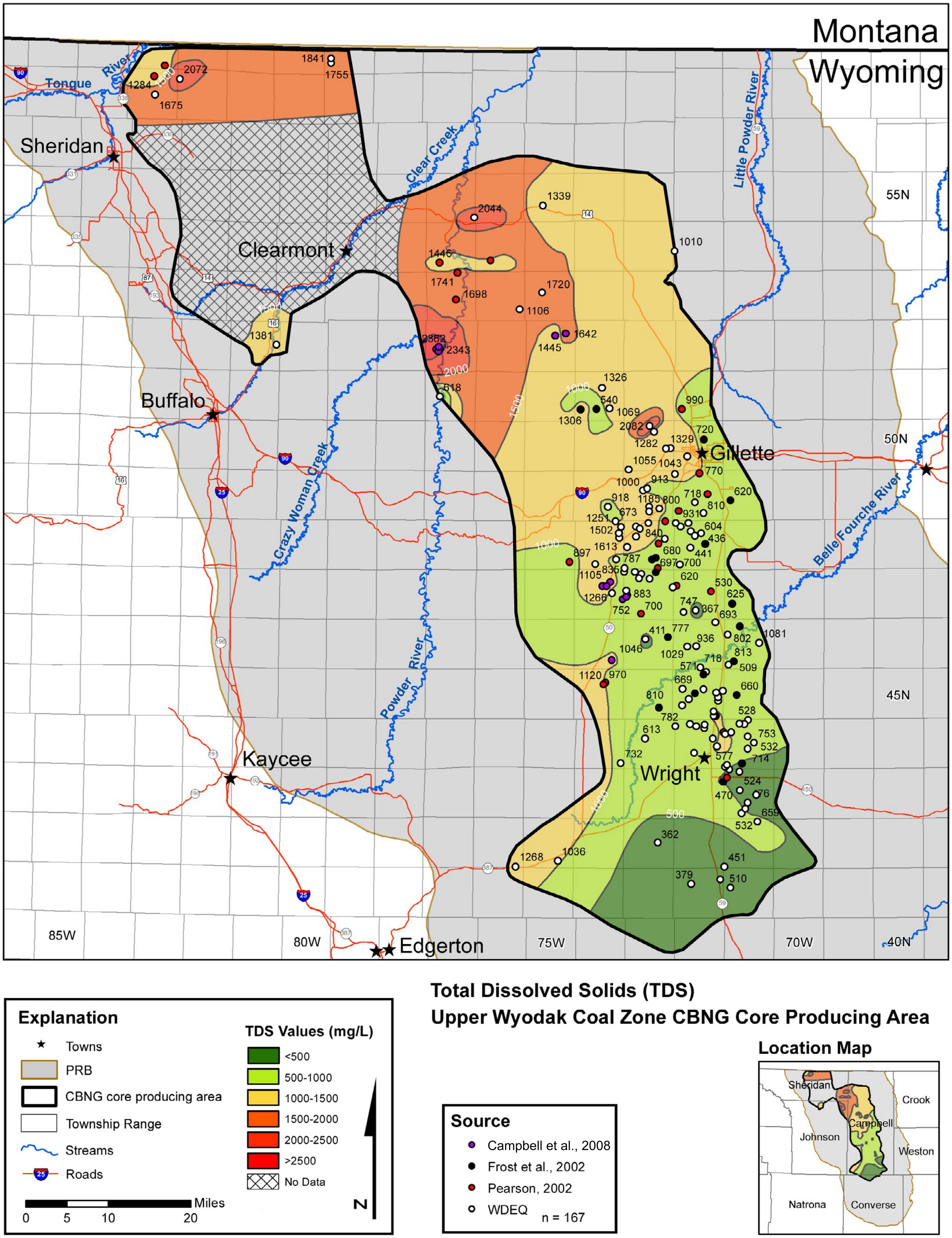

Figure 11. Spatial distribution of TDS for produced water from the Upper Wyodak coal zone within the core producing area. Note increase in TDS from southeast to northwest.

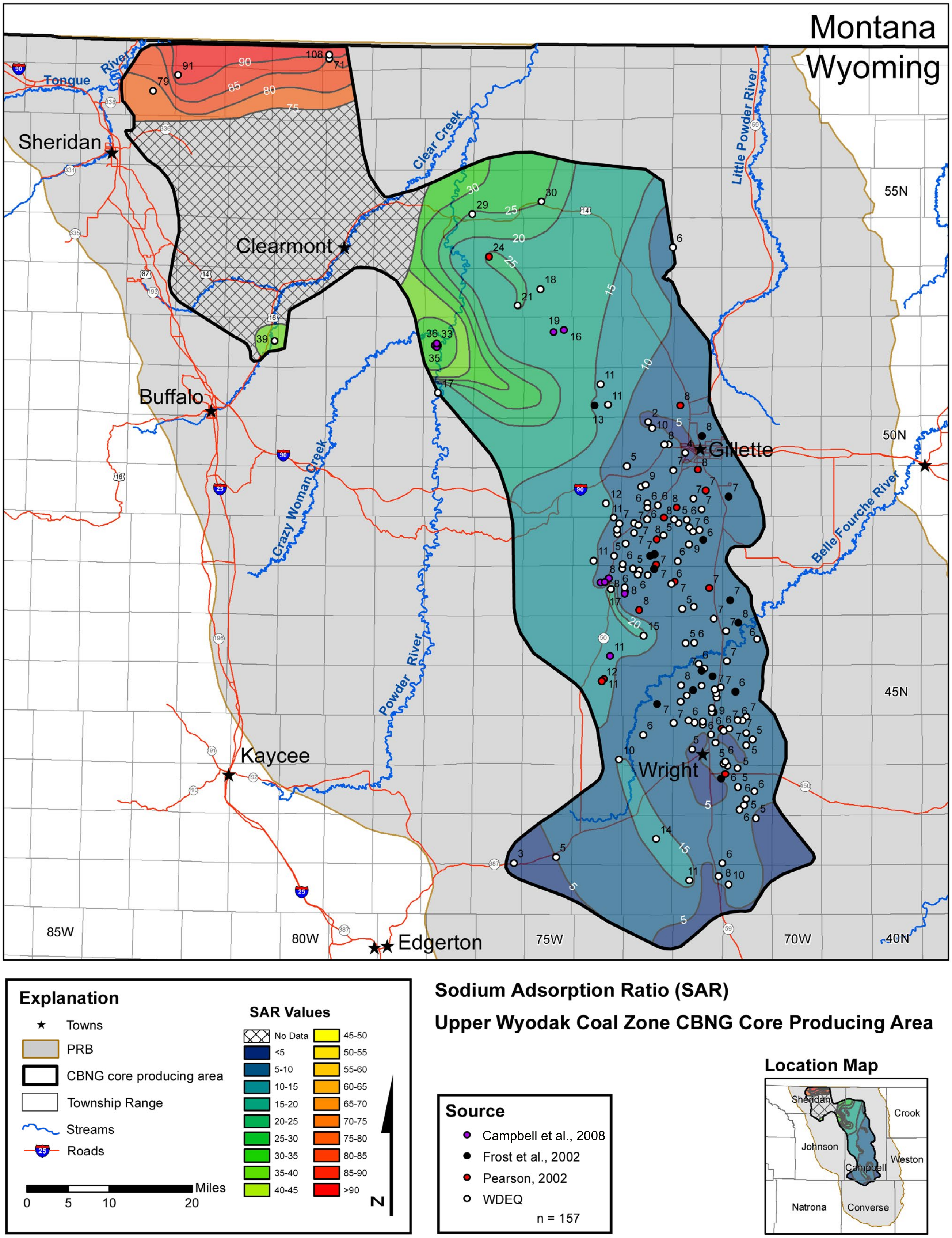

Figure 12. Spatial distribution of SAR for produced water from the Upper Wyodak coal zone within the core producing area. Note increase in SAR from southeast to northwest.

upon analyses of water samples from 169 wells (Figure 6; Appendix A). TDS concentrations for the Upper Wyodak CPA range from 362 to 3,046 mg/L with a mean value of 917 mg/L (Figure 11); these are slightly lower than the Wyodak Rider CPA in the same vicinity. SAR range from 2.2 to 108 with a mean value of 10.7. The highest SAR in the Upper Wyodak CPA is found at the Wyoming-Montana state line (Figure 12). TDS and SAR increase along groundwater flow direction from the south to the north (Figures 11, 12).

Lower Wyodak

The Lower Wyodak CPA was determined based on the location of 2,211 wells. These wells cluster in four areas (Figure 13): CPA-1 is located in Sheridan County south of the Wyoming-Montana state line and includes 48 wells; all have multi-zone completions. CPA-2 is located in Sheridan, Campbell, and Johnson counties, contains 1,604 wells, and represents the production area of the Lower Wyodak coal zone north of where the Upper and Lower Wyodak coals coalesce. CPA-3 is mainly in Johnson County. It includes 82 wells of which all but one well is shut-in or abandoned. Only 10 of the 82 wells drilled in CPA-3 report any gas production and none of the wells have reported commercial gas production. CPA- 4 is located south of the Upper and Lower Wyodak merger and contains 469 wells (Figure 13). Wells in this area are clustered in the two regions where the Canyon coal of the Lower Wyodak exceeds ten feet in thickness. Since CPAs 1 and 3 have produced little to no gas, we dash the boundaries of these areas on Figure 13.

Wells completed in the Lower Wyodak coal zone have produced 174 BCF of gas and 330 MmBbls of water. The cumulative water to gas ratio for the Lower Wyodak CPA is 1.9 Bbls of water per MCF of gas (Table 2). Water to gas ratios are highest in new production areas, on the western edge of CPA-2, where the wells have multiple completions in the Canyon, Cook, and Wall coal zones (Figures 5c and 13).

The chemical composition of produced water from the Lower Wyodak coal zone was characterized on the basis of water sampled from 30 wells (Figure 6, Appendix A). TDS ranges from 537 mg/l to 1,611 mg/L with a mean value of 1,118 mg/L. The TDS concentrations increase from the south to north along the direction of groundwater flow (Figure 14). SAR values range from 4 to 27, with a mean value of 11.8 (Figure 15).

Cook

In the PRB, 3,795 wells produce from the Cook coal zone (Table 2). The Cook CPA (Figure 5-d) encompasses 3,415 of those wells. Approximately half (1,489) of these wells have commingled completions with other coal zones. Cumulative gas and water produced from the Cook coal zone was based only on the 2,308 wells that have single completions in the Cook coal zone; thus, the compilation of the amount of produced gas and water underestimate production. The single completion wells in this coal zone have produced more than 155 BCF of gas and 238 MmBbls of water, a water to gas ratio of 1.5 (Table 2). The Cook CPA is broken into two areas: the Cook CPA-1 is a smaller area located in Sheridan County (T58-57N and R79-81W); the Cook CPA-2 extends across Sheridan, Campbell, and Johnson counties (T49-58, R 73-78W) (Figure 16).

Water quality data comes from 14 analyses of produced water from the Cook coal zone, all but one of which lie within CPA-2. The TDS of the single sample from CPA-1 is 2,075 mg/L. TDS of water samples from CPA-2 range from 1,004 mg/L to 2,714 mg/L, with a mean of 1,864 mg/L (and with a high standard deviation of 720). The values increase from the eastern margin of the Cook CPA-2 and are the highest in the southwest corner (Figure 17). The single

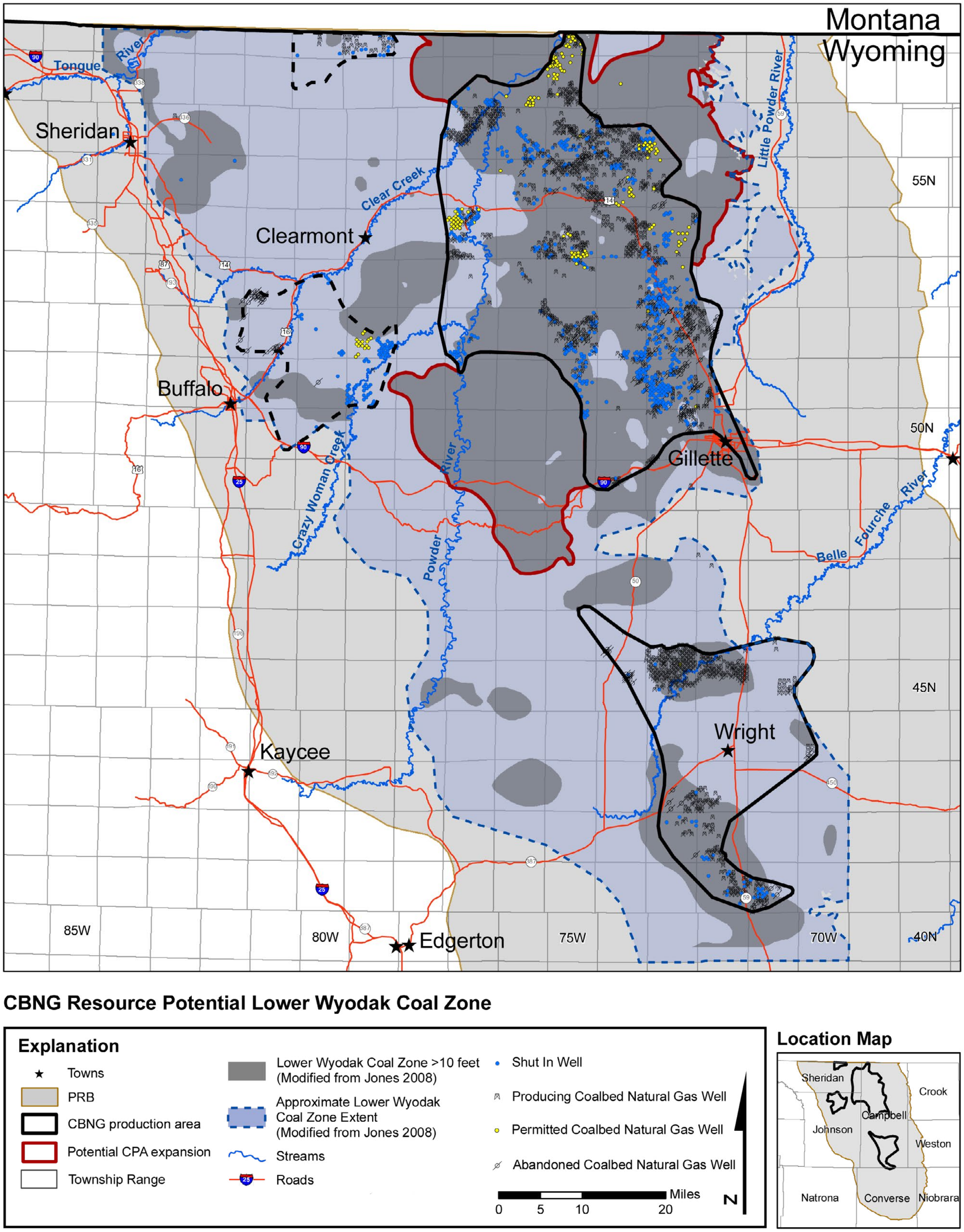

Figure 13. CBNG Resource Potential of the Lower Wyodak coal zone, showing present core producing areas (CPA-1 through -4, outlined in thick solid and dashed black lines). Also shown are producing, shut in, abandoned and permitted CBNG wells, and areas for possible future CBNG development of the Lower Wyodak coal zone (outlined in thick red line). Coal thicknesses and coal zone extent is updated from Jones (2008).

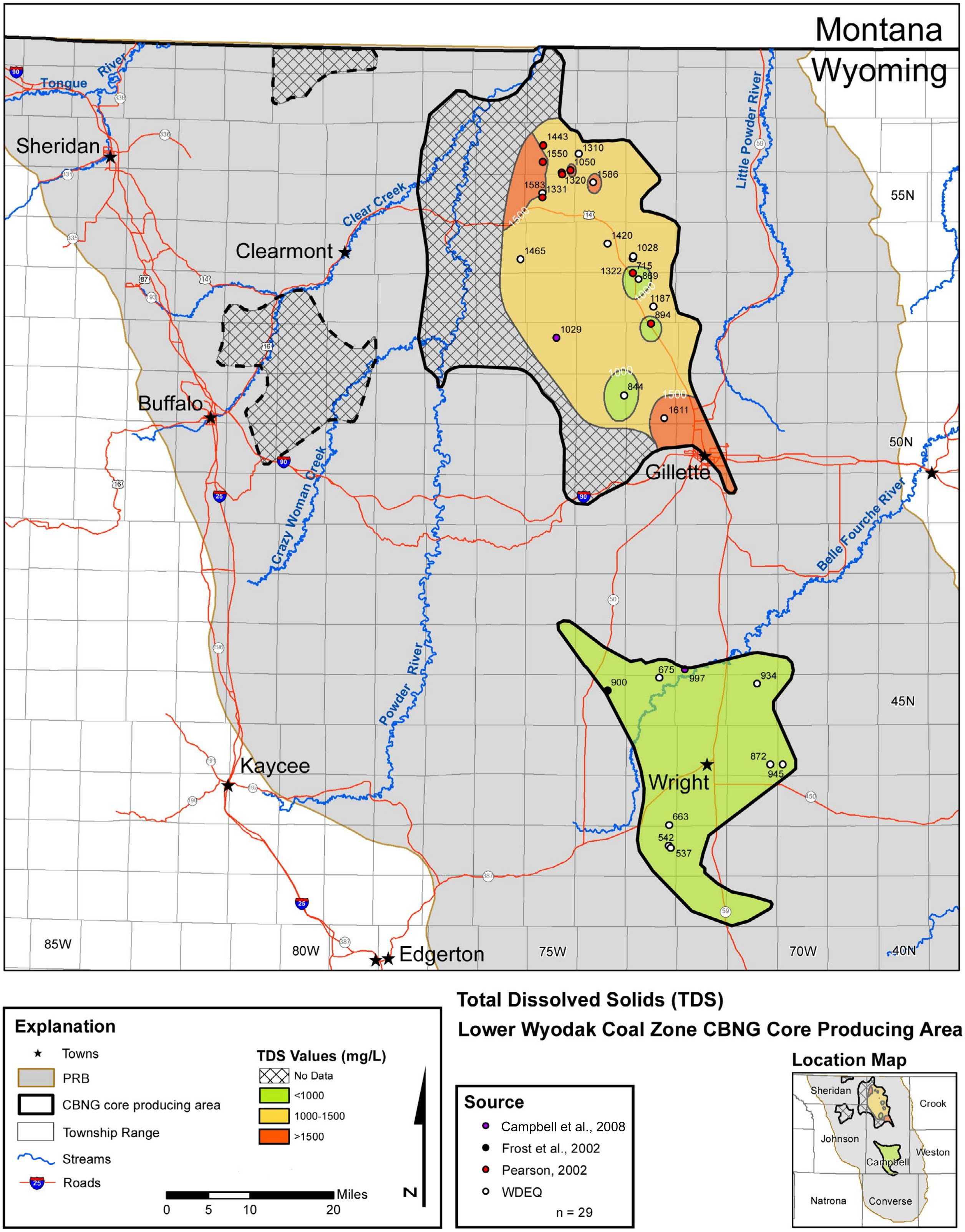

Figure 14. Spatial distribution of TDS for produced water from the Lower Wyodak coal zone within the core producing area. Note lower TDS in CPA-4 near Wright compared to CPA-2 north of Gillette.

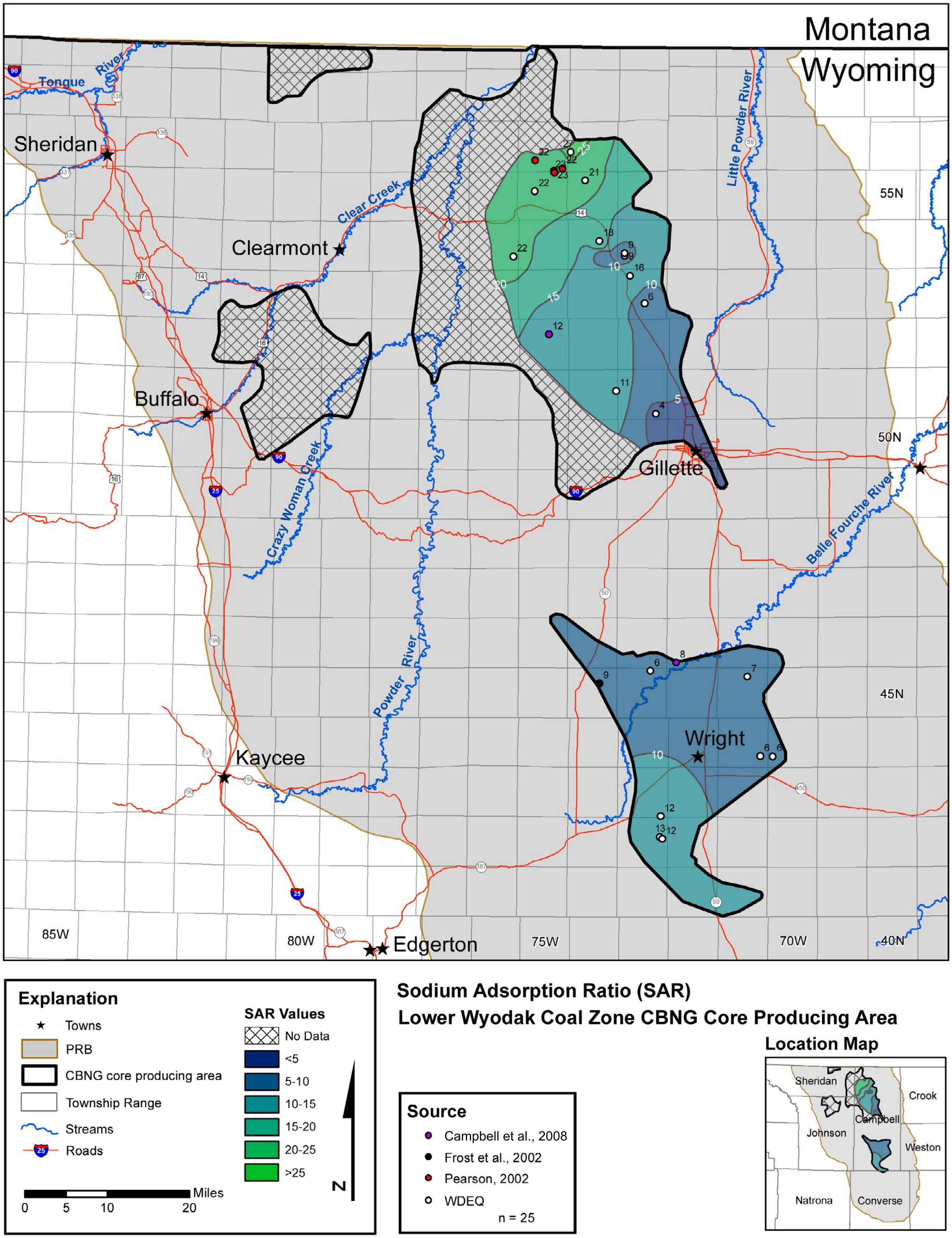

Figure 15. Spatial distribution of SAR for produced water from the Lower Wyodak coal zone within CPA-4 and CPA-2.

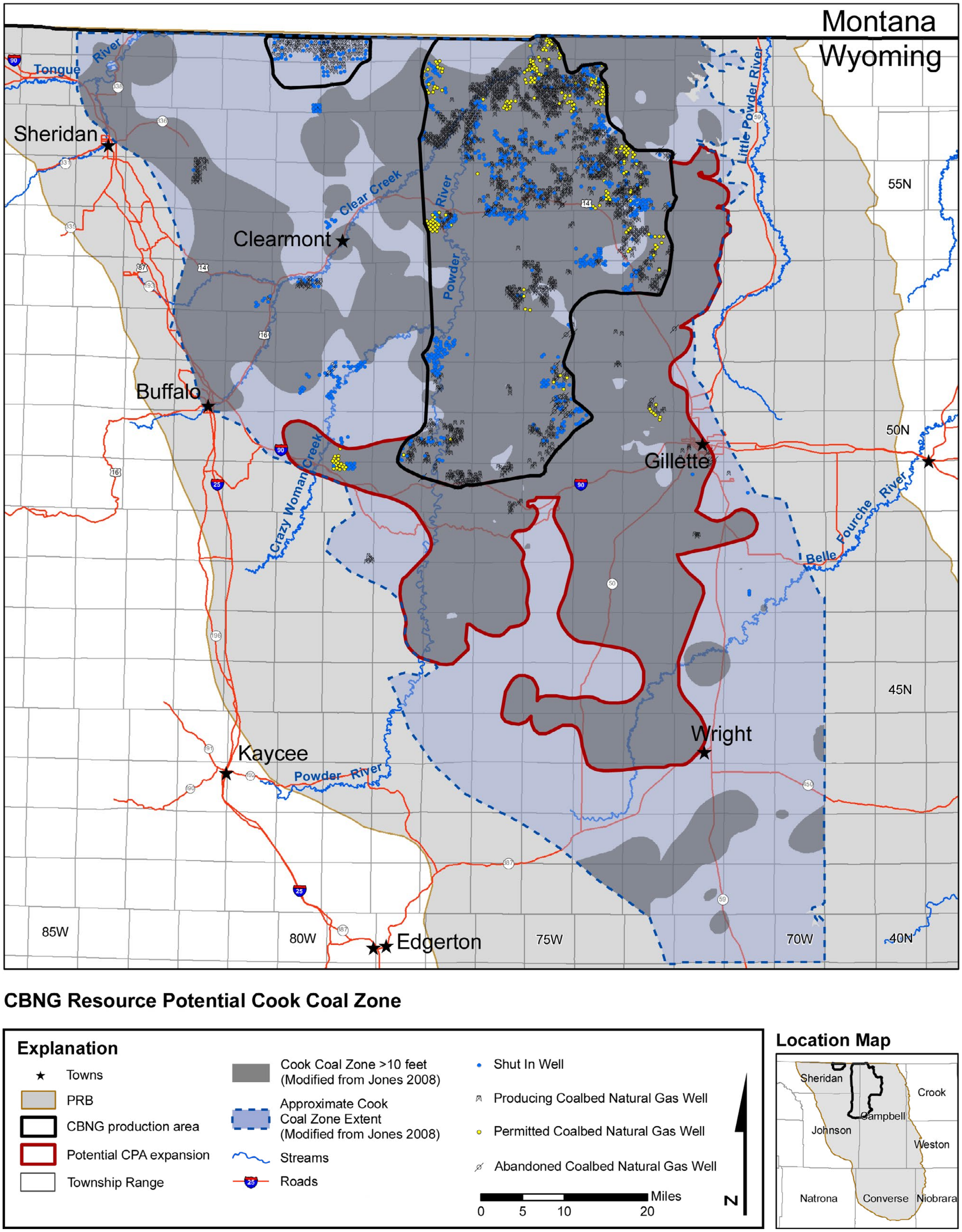

Figure 16. CBNG Resource Potential of the Cook coal zone, showing present core producing area (outlined in thick black line), producing, shut in, abandoned and permitted CBNG wells, and areas for possible future CBNG development of the Cook coal zone (outlined in thick red line). Coal thicknesses and coal zone extent is updated from Jones (2008).

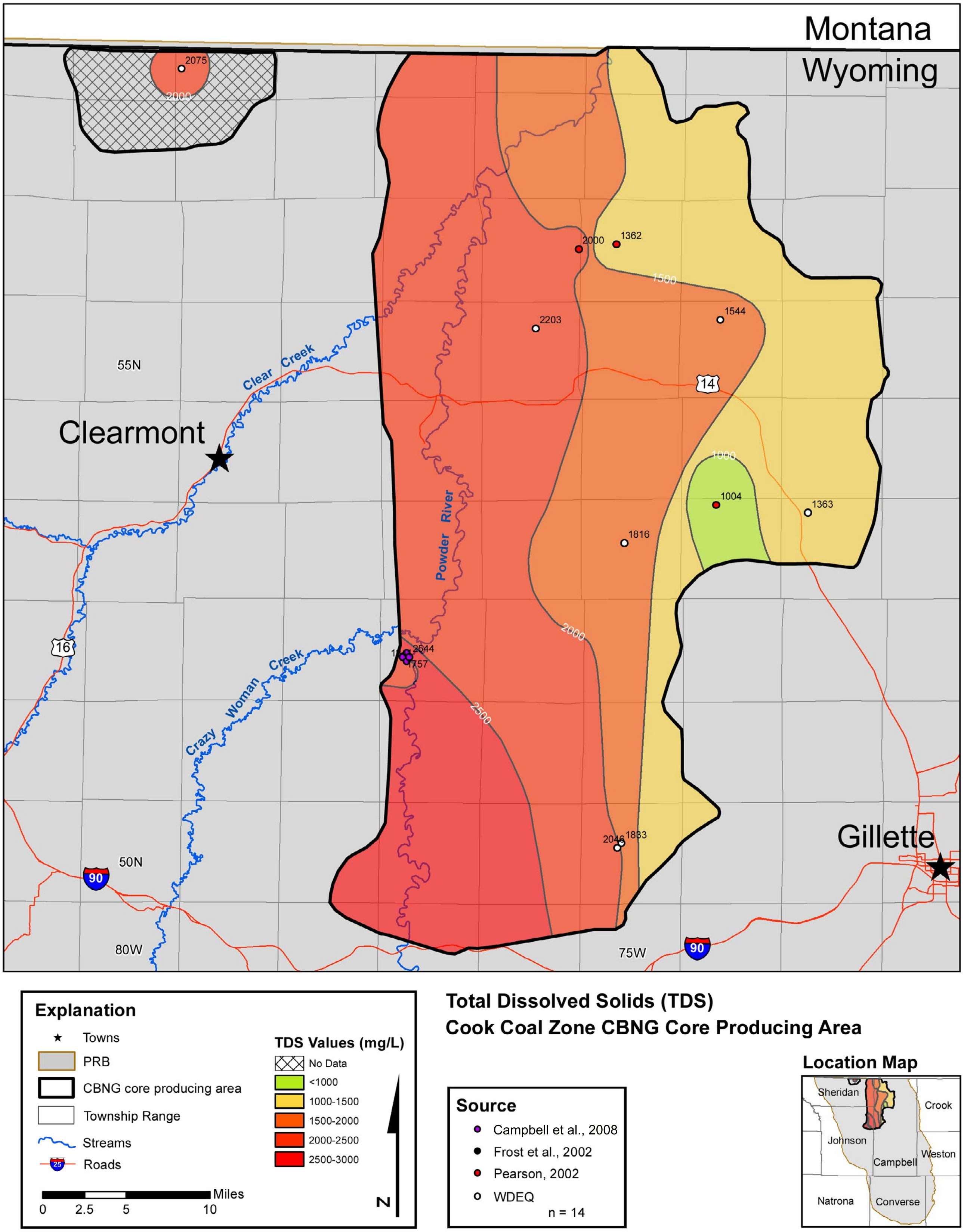

Figure 17. Spatial distribution of TDS for produced water from the Cook coal zone within the core producing area. Note increase in TDS from east to west.

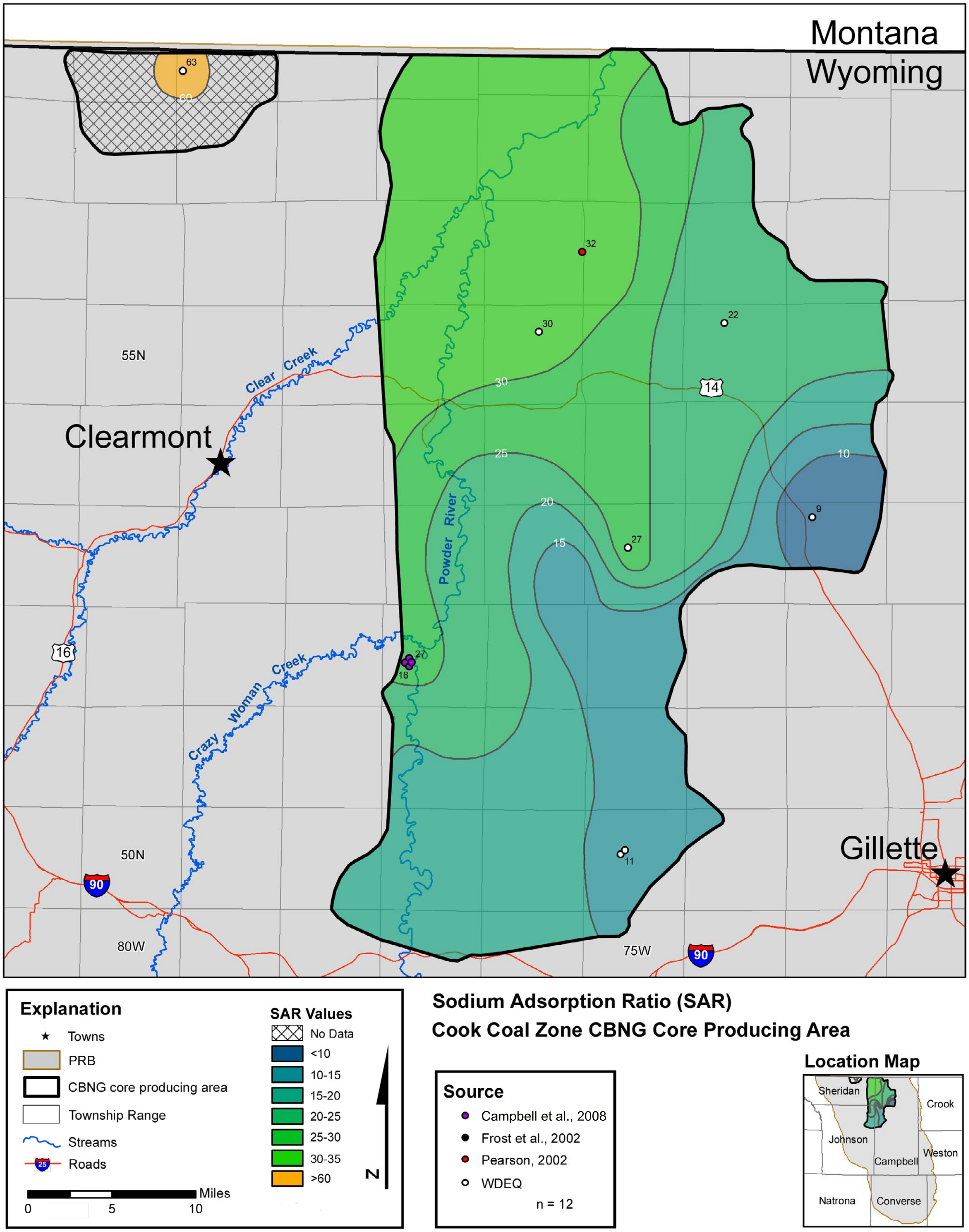

Figure 18. Spatial distribution of SAR for produced water from the Cook coal zone within the core producing area. Note increase in SAR from east to west.

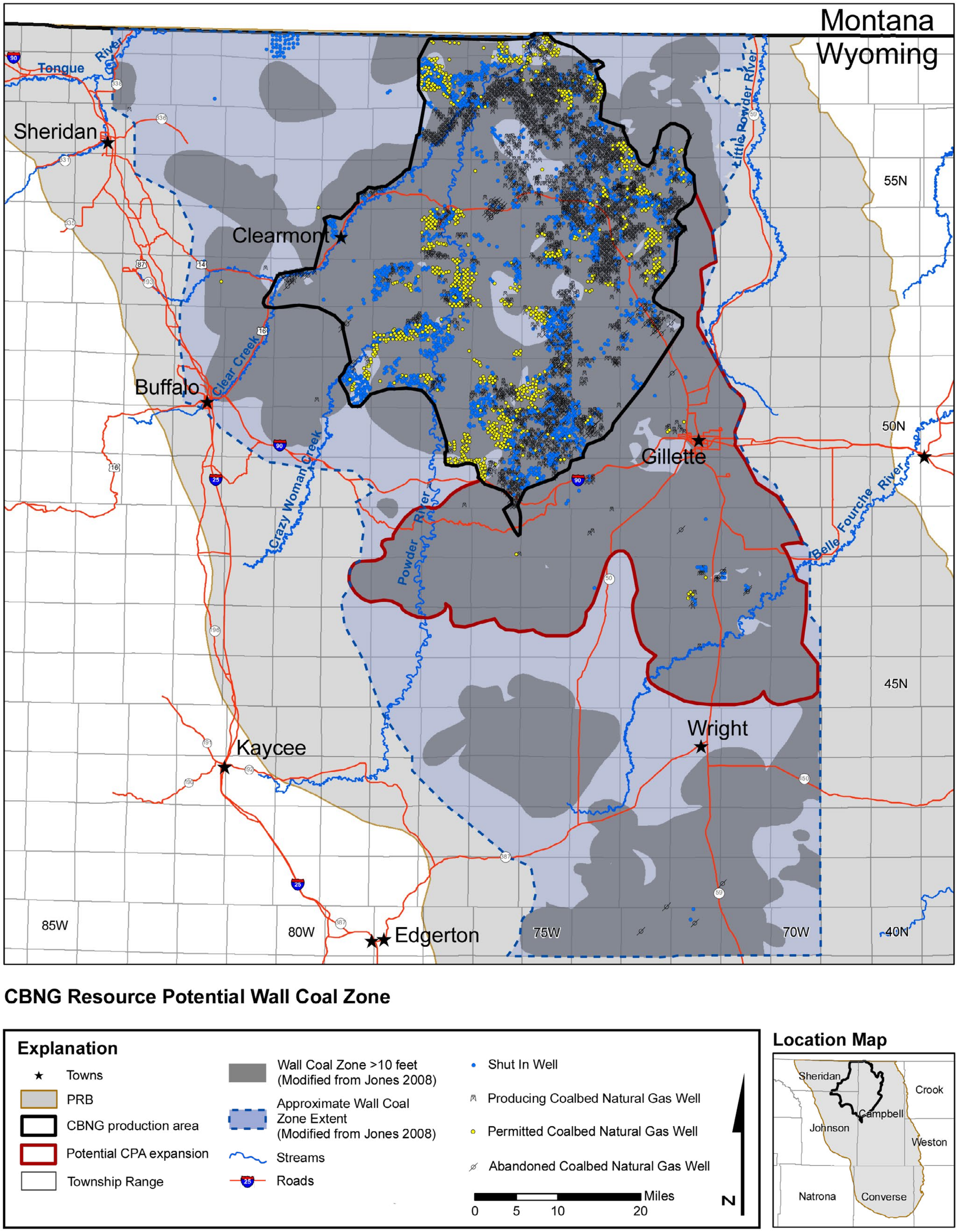

Figure 19. CBNG Resource Potential of the Wall coal zone, showing present core producing area (outlined in thick black line), producing, shut in, abandoned and permitted CBNG wells, and areas for possible future CBNG development of the Wall coal zone (outlined in thick red line). Coal thicknesses and coal zone extent is updated from Jones (2008).

SAR value from CPA-1 is 63. In the CPA-2 the SAR ranges from 9 to 62.7, with a mean value of 22.3. SAR values increase from the southeast to the northwest of the CPA-2 (Figure 18).

Wall

A total of 6,551 wells are completed in the Wall coal zone (Table 2). The Wall CPA (Figure 5e) encompasses 93 percent (6,138) of these. A total of 1,092 Wall coal zone wells have commingled completions with stratigraphically higher coal zones. Cumulative gas production from the single completion wells in the Wall coal zone is 130 MCF and cumulative water production is 495 MmBbls. These data yield water to gas ratio of 3.8 Bbls/MCF, the highest of any coal zone (Table 2).

Water quality data is available from 15 samples. TDS range from 586 to 2664 mg/L, increasing from east to west. The highest TDS are observed in the southwest of the Wall CPA (T51N and R77W; Figure 20). The Wall coal zone has an average TDS of 1,531 mg/L. Sodium adsorption ratios were calculated from the laboratory measurements of 12 samples and range from 9.6 to 74.3 with an average value of 21.3 (Figure 21).

Discussion

Based on the results above, we summarize the variations in CBNG water quality within the PRB and discuss possible beneficial uses for these waters. We then identify potential areas of future gas development and estimate the quality of water that will be produced along with this natural gas.

CBNG Water Quality

The quality of water produced with CBNG determines beneficial use of that water. For example, water used for irrigation must meet certain salinity and sodicity thresholds that vary depending upon soil type and the plant species cultivated. Concern that surface discharge of water produced with CBNG may degrade surface water quality led Montana to promulgate water quality standards under the Clean Water Act (CWA) for rivers that flow from the area of production in Wyoming into Montana (Clean Water Act, 1972; Montana Board of Environmental Review, 2002 and 2005). Montana named irrigated agriculture as the beneficial use most sensitive to development of CBNG and the associated discharge of produced water. Montana identified electrical conductivity (a proxy for TDS) and SAR as principal constituents of concern in CBNG produced water. The Montana regulations were subsequently challenged and in October 2009, the U.S. District Court vacated the EPA's approval of these standards (Frost and Mailloux, 2011). Nevertheless, concern remains that CBNG produced waters have the potential to degrade surface watersheds, impacting beneficial use (Horpestad et al., 2001). In addition, the spatial variability in quality of produced water in the PRB suggests that certain uses of produced water may be possible in some areas but not in others.

By describing the spatial patterns in salinity and sodicity of produced water within each coal zone, we can predict TDS and SAR for potential new areas of CBNG development. We can make some general observations based upon our results and analysis above. First, TDS and SAR generally increase from southeast towards the center of the basin. The trends are similar in all coal zones; this suggests that areas of high TDS and SAR are not coal zone specific but are related to their general position along groundwater flow path. Many of these coals outcrop in close proximity, thus the distance along the flow path is similar for all coal zones. For this reason the water quality of produced water correlates with geographic location, regardless of the coal zone from which the water is extracted. TDS and SAR are generally highest for water produced near the course of the Powder River, north of the confluence with Crazy Woman

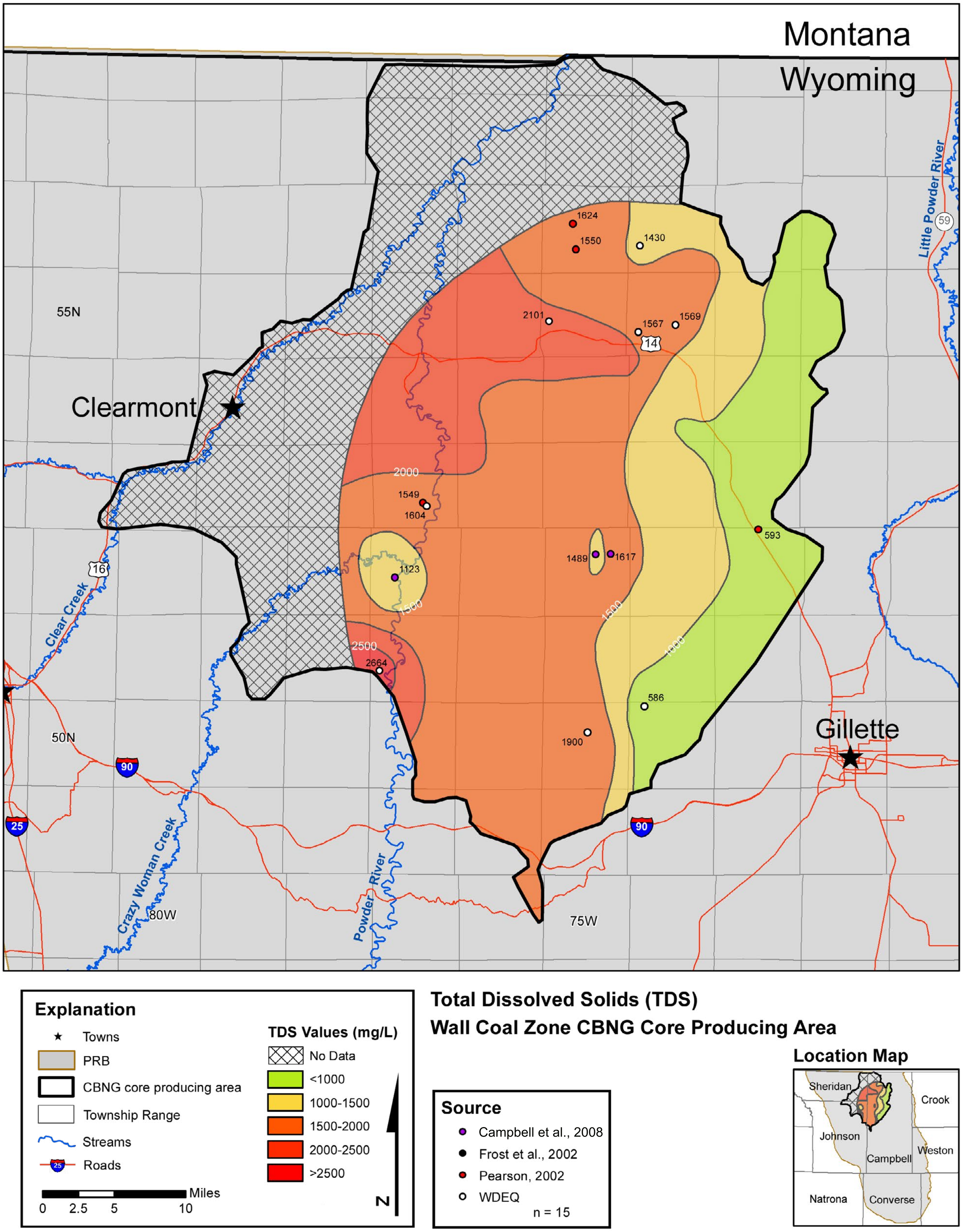

Figure 20. Spatial distribution of TDS for produced water from the Wall coal zone within the core producing area.

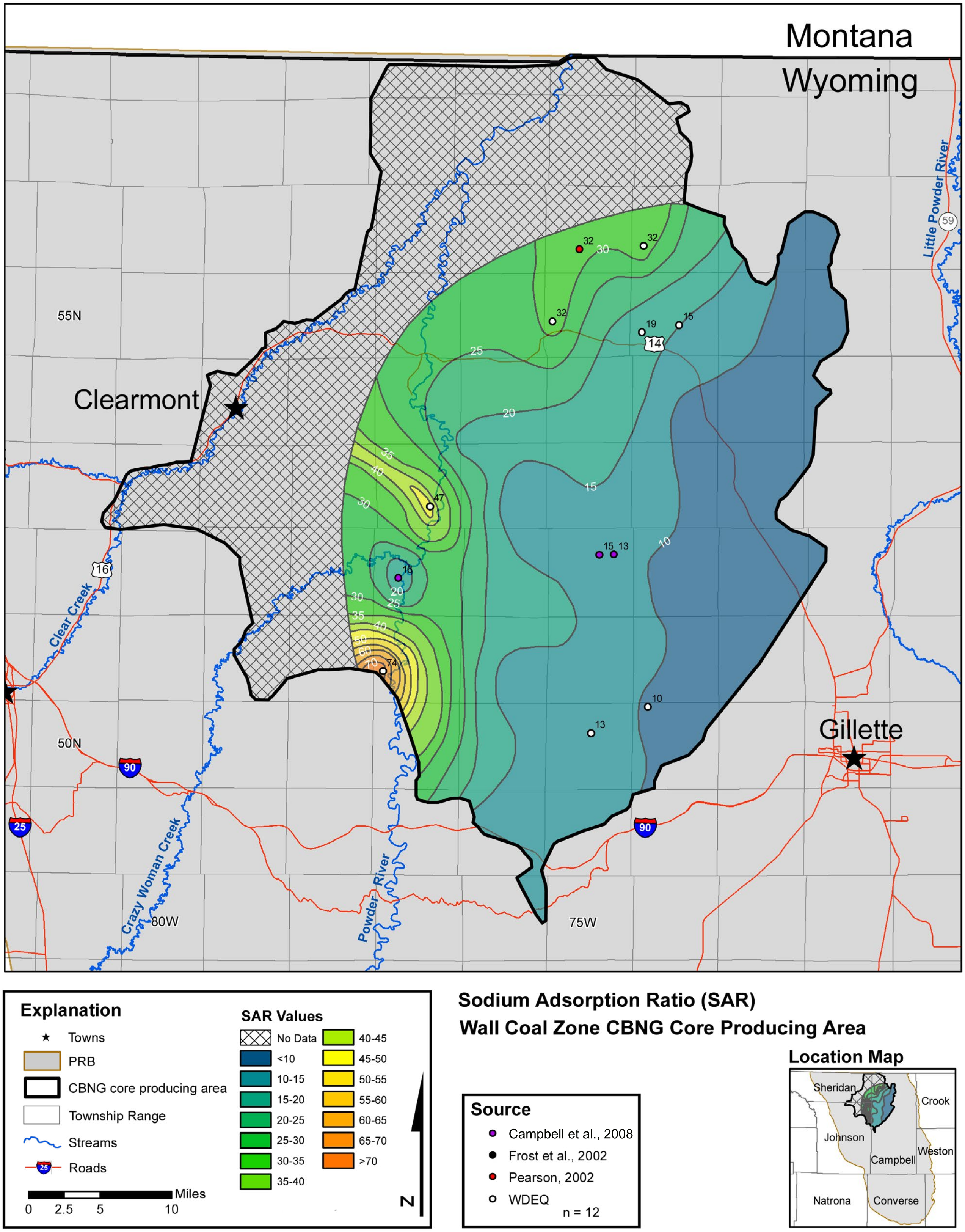

Figure 21. Spatial distribution of SAR for produced water from the Wall coal zone within the core producing area. Note increase in SAR from east to west.

Creek. In addition, relatively high TDS have been measured in produced water from the Upper and Lower Wyodak coal zones in a small area northwest of Gillette (Figures 11 and 14). We note some important gaps in our dataset; for example, no water quality data are available for the Lower Wyodak coal zone in the area in the center of the basin where TDS and SAR tend to be high in all other coal zones (Figure 13).

Beneficial Use of Produced Water

The Wyoming Department of Environmental Quality (WDEQ) provides general guidance on water quality standards for different beneficial uses of groundwater wells, including domestic water (Class I), water for agriculture (Class II), and water for livestock (Class III). Other uses include water for fish and aquatic life and water for industry (WDEQ, 2005). Waters meeting Class I, II, or III standards must contain no more than specified threshold amounts of a variety of constituents. Among these, domestic water should have no more than 500 mg/L TDS. Waters meeting a standard for agriculture must have SAR of 8 or less and a TDS no greater than 2,000 mg/L (WDEQ, 2005). According to the WDEQ (2005), waters used for livestock may have up to 5,000 mg/L TDS.

Other sources suggest that more saline and sodic water may be used for agriculture with careful management practices (Rhoades, 1982; Hoffman et al., 1990; Hanson, 1999; and Bauder et al., 2007). One important control is the relationship between TDS and SAR; as we noted in the methods section above, a higher SAR may be tolerated if salinity also is higher. Recently the WDEQ have implemented new monitoring guidelines in some of the irrigated drainages within the PRB (Pumpkin Creek, Willow Creek, and Dead Horse Creek). The heightened monitoring requirements call for monthly to quarterly sampling of SAR and electrical conductivity, a proxy for TDS, among other constituents, which may include sodium, calcium, magnesium, potassium, chloride, sulfate, bicarbonate, and carbon isotopes (WDEQ, 2011). Although monitoring of several constituents is required, thresholds are primarily based on the relationship between SAR and EC[2].

Figure 22 relates TDS and SAR of PRB produced water. Examination of this plot shows that produced water from the Upper Wyodak coal zone generally is the least saline and sodic, and most wells meet the WDEQ standard for agricultural use. In contrast, produced water from the Lower Wyodak is similarly dilute but is more sodic, and few analyses meet the WDEQ standards for agricultural use. Produced water from the Wyodak Rider can be quite saline, but water from most of the wells sampled falls below the line above which soil structure is affected to an extent that infiltration may be decreased (Rhoades, 1982). Water from Cook and Wall coal zones have variable TDS and SAR. Few meet the WDEQ standards for agricultural use and many exceed the infiltration threshold. The beneficial use of these waters could be expanded through various water treatment and/or soil amendment practices. Clearly it is necessary to examine the spatial distribution of water quality from each of these coal zones to determine the beneficial use and or treatment options that are suitable for produced water from any given location.

Future Potential Development

Future CBNG development may be best focused by locating new wells in areas with a probability of high gas production, low water production, and acceptable water quality. This study reveals that for some coal zones this will be achieved by additional production within

[2] *For additional information on how/why the aforementioned constituents may be relevant to identifying and tracing CBNG produced water, the reader is referred to Brink and Frost (2007), Brinck et al. (2008), Campbell et al. (2008), Frost et al. (2010), Mailloux, et al. (in press), McLaughlin et al. (2011), Quillinan and Frost (2011), and Quillinan (2011b).*

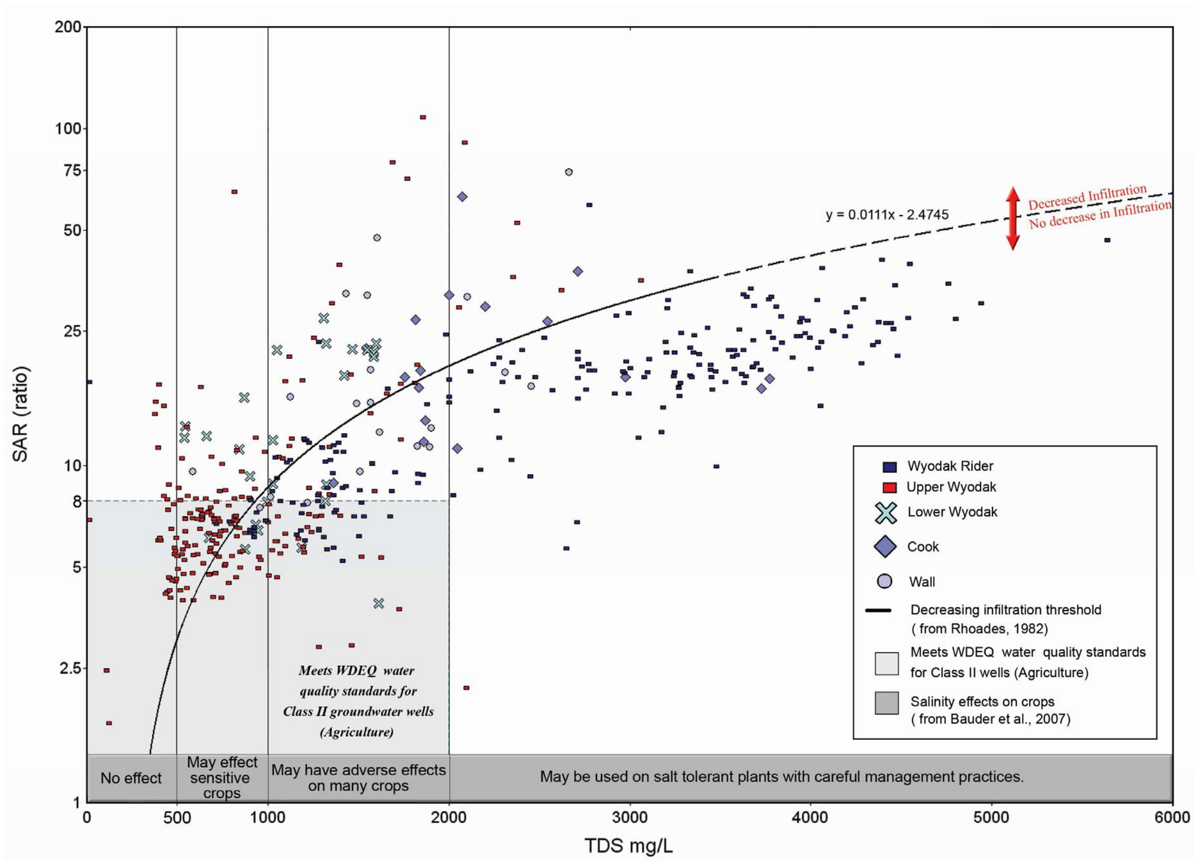

Figure 22. SAR and TDS concentrations of CBNG produced water from the Powder River Basin. Data is from Appendix A.

the present CPA. For other coal zones, it may be more advantageous to expand the CPAs, as described in detail below.

Wyodak Rider

To date, the Wyodak Rider coal beds have been targeted by more wells than any other coal zone. Production has focused on the thickest coal, the Big George, because of its thickness and relatively high gas content. The current core producing area covers roughly 65 percent of the area with coals that exceed 10 ft. or greater thickness (Table 3). On Figure 6, a red outline identifies a few areas that may be suitable for expansion outside of the current CPA. One is an area north of the present CPA, about halfway between Clearmont and Gillette. In this area, there are coals with thicknesses greater than 10 feet. Figures 8 and 9 suggest that TDS may be between 1,500 and 4,000 mg/L, and SAR values could range from 20-30. We note, however, that previous wells drilled in this area, albeit few, have been shut-in or abandoned. It would be important to establish why these wells are no longer in production before undertaking additional drilling in this area.

Another area that may be suitable for future production is located northeast of Kaycee and west of the current CPA. TDS and SAR of produced water from this area are estimated to be 2,500-3,000 mg/L and 20, respectively (Figure 8 and 9), which would be suitable for irrigating salt tolerant crops (Figure 23). Finally, expansion of Wyodak Rider production to the east around Wright and extending toward Gillette would likely be associated with dilute, low SAR produced water with TDS <1,000 mg/L and

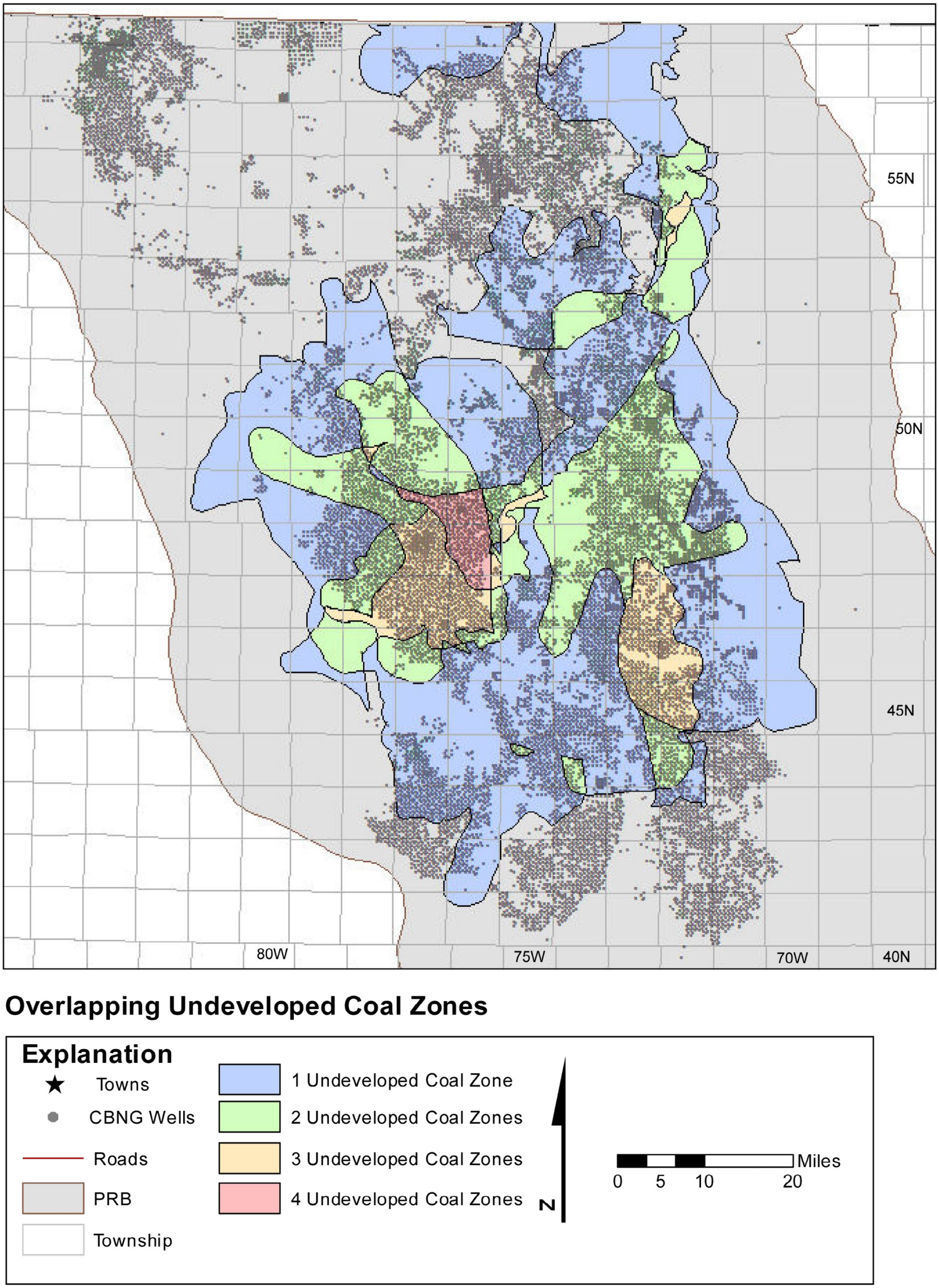

Figure 23. Areas of overlapping, undeveloped coal zones. Colors highlight the number of undeveloped coal zones that underlie an area. Note that much of the undeveloped areas lie within areas of current development, thus future development could use infrastructure that is already in place.

SAR <10. Water to gas ratios in this area are also low (Figure 5a). This water will likely meet WDEQ water quality standards for irrigation, but may exhibit adverse effects on soil structure. Blending with higher salinity water produced elsewhere from the Wyodak Rider coal zone could lower the risk of soil degradation.

In addition, there is potential for infill drilling within the Wyodak Rider CPA. Figure 7 illustrates active permitted wells as yellow dots. Figures 8 and 9 can be used to estimate the produced water quality from these future wells; water quality should be best for those wells planned for the southern part of the CPA.

Upper Wyodak

The Upper Wyodak CPA encompasses approximately 58 percent of the Upper Wyodak coal zone (Table 3). Most of the undeveloped area of the Upper Wyodak lies beneath current Wyodak Rider-Big George production, west of current Upper Wyodak production (Figure 10). Expansion in this area would move towards the basin axis and away from recharge. Trends observed by Rice et al. (2000) and Campbell et al. (2008), and further supported by this study, suggest that further western expansion of the Upper Wyodak coal beds will lead to higher TDS and consequently higher SAR values. Lack of well data to the west make estimates uncertain but based on water quality data from the Wyodak Rider in the same area; we predict that TDS and SAR from the Upper Wyodak could be higher than water currently produced from the Wyodak Rider. Wells with water to gas ratios greater than 25 also occur in higher density in this direction, perhaps reflecting greater hydrostatic pressures in the coal beds farther down dip.

Very few wells are permitted for immediate development in the Upper Wyodak coal zone (Figure 10). These wells will likely produce water with TDS less than 1,500 mg/L and SAR ranging from 10-15. Water of this quality meets the WDEQ standard for agricultural use and lies beneath the threshold above which soil structure is affected such that infiltration is reduced (Figure 22).

Lower Wyodak

Approximately 50 percent of the Lower Wyodak coal zone where coals exceed 10 feet thick remains to be developed (Table 3; Figure 13). The locations of permitted wells indicate where immediate future development in the Lower Wyodak CPA will take place (Figure 13). The probable quality of produced water can be estimated from the spatial variations in existing data available from the eastern part of CPA-2 (Figures 14 and 15). If the CPA were to expand to the north and northeast, TDS of produced water may range from 1,000-1,500 mg/L with a SAR likely varying from about 10 to potentially above 25. Estimates for a southwest expansion are more problematic due to the lack of data in this area. However, elevated TDS is measured in all other coal zones in this area (Figures 8, 11, 17, and 20) suggest similarly high TDS is likely for the Lower Wyodak coal zone as well.

Cook and Wall

Both the Cook and the Wall coal zones have large areal extents with a majority of coal greater than 10 feet thick (Figures 16 and 19). Nearly 70 percent of the Cook coal zone and 65 percent of the Wall coal zone has not yet been developed (Table 3). Relatively little is known about these two deepest coal zones. Most of the potential area for future development in these zones is southeast of the current CPAs, up-gradient from groundwater flow. This would suggest that future development of these coals will produce water of equal or lower TDS than is currently produced. Water to gas ratios for these two coal zones are lowest in the northeast corners of the respective CPA (Figures 5d and 5e), and bode well for developing these areas.

Future potential development of all coal zones. As water quality regulation and ultimately economics tighten on the CBNG industry, it is becoming more common that wells are completed in multiple coal zones. The CBNG resource maps in this study outline areas of potential expansion (red outlines on Figures 7, 10, 13, 16, and 19). Many of these areas overlap, and thus identify locations of potential multiple-zone targets. The intersections of these areas have been compiled on Figure 23, and indicate the number of coal zones that remain to be developed in a particular location. It should be noted that even though multiple coal zones remain to be developed within these areas, CBNG wells in the area may already be producing from one or more coal zones. Thus the infrastructure is in place for developing additional coal zones. For example, in the center of the basin, the map indicates that four overlapping coal zones could be developed (Figure 23). Existing wells within this area are producing from the Wyodak Rider coal zone (Figure 7). The four additional coal zones that lie below the Wyodak Rider coal zone will likely yield produced water that is of equal or better quality than water produced elsewhere from these zones. This example suggests a strategy by which CBNG development in the PRB may continue to increase with minimal surface disturbance, producing water that could potentially be put to beneficial use.

Conclusions

Classifying wells by coal zone and plotting these locations geospatially, enable definition of "core producing areas" for the five main CBNG-producing coal zones. Furthermore, we are able to predict the water quality for produced water recovered from these coal zones, and identify areas of low water to gas ratios, all of which may indicate favorable conditions for future development.

For all coal zones, TDS and SAR generally increase from the southern and eastern margins of the PRB towards the basin axis. Detailed examination of water quality information presented spatially and by coal zone in this study can be used to estimate produced water quality for future development. Although there are some differences that are related to the coal zone from which water is produced, in general, the geographic location of a well is more predictive of TDS and SAR than the coal zone in which it is completed.

Common constituents used to determine beneficial use of produced water, particularly for irrigation, are SAR and TDS. These constituents are correlated: water with high SAR may be used for irrigation without impacting soil quality if TDS is also high. Our examination of 337 analyses of produced water from the PRB suggests that most produced water in the PRB water if integrated with careful management practices, could be used to irrigate salt-tolerant plants. We refer the reader to Brinck and Frost (2009) for a more detailed description of the impacts of irrigating with produced water in the PRB and the management practices required to maintain soil health.

Primarily completed in the Big George coal bed, the Wyodak Rider coal zone hosts more wells than any other coal zone. This coal zone has produced more gas than any other coal zone and has the lowest water to gas ratios. The Upper and Lower Wyodak coal zones were developed prior to the Wyodak Rider coal zone. They have slightly higher water to gas ratios than the Wyodak Rider. The coal zones that have produced the least amount of gas are the Cook and Wall coal zones, although it is important to note that many of these wells share multi-zone completions with other coal zones, making total gas production estimates from the Cook and Wall coal zones difficult to quantify.

Large areas for each coal zone remain to be developed inside and outside of their current core producing area. With the information presented in this study, future development in the PRB could focus on areas where multiple production intervals are present and the water quality can be estimated. This approach would continue the development of the vast CBNG resource, utilize existing infrastructure, minimize surface disturbance, and produce water most suitable for beneficial use.

Acknowledgements

The authors wish to acknowledge Tomas Gracias, Jim Rodgers, and Chamois Andersen at the Wyoming State Geological Survey who helped create the maps, figures, and layout presented in this report. This report received a helpful and constructive review from Ralph Topper, Senior Hydrogeologist at the Colorado Division of Water Resources and Michael A. Williams, Senior Environmental Professional at Marathon Oil Company. We also want to thank Mary Kate McCarney for technical editing.

References

Bartos, T. T., and Ogle, K. M., 2002, Water quality and environmental isotopic analyses of ground-water samples collected from the Wasatch and Fort Union formations in areas of coalbed methane development—Implications to recharge and ground-water flow, eastern Powder River Basin, Wyoming: U.S. Geological Survey Water-Resources Investigations Report 02-4045, 88 p.

Bauder, T. A., Waskom, R. M., Davis, J. G., 2007, Irrigation Water Quality Criteria, Crop Series no. 0.506, Colorado State University Cooperative Extension: Fort Collins, CO, 4 p .

Brinck, E.L., Drever, J.I., and Frost, C.D., 2008, The geochemical evolution of water co-produced with coal bed natural gas in the Powder River Basin, Wyoming: Environmental Geosciences, v. 15, no. 4, p. 153-171.

Brinck, E.L., Frost, C.D., 2009, Evaluation of amendments used to prevent sodification of irrigated fields: Applied Geochemistry, v. 24, p. 2113-2122.

Campbell, C.E., Pearson, B.N., and Frost, C.D., 2008, Strontium isotopes as indicators of aquifer communication in an area of coal bed natural gas production, Powder River Basin, Wyoming and Montana: Rocky Mountain Geology, v. 43, no. 2, p.149-175.

Clean Water Act of 1972, 33 U.S.C. § 1251 (2010).

Frost, C.D., Brinck, E.L., Mailloux, J., Sharma, S., Campbell, C.E., Carter, S.A., Pearson, B.N., 2010, Innovative approaches for tracing water co-produced with coalbed natural gas: applications of strontium and carbon isotopes of produced water in the Powder River Basin, Wyoming and Montana, in K.J. Reddy, ed., Coalbed methane: energy and environment: New York, Nova Science Publishers, p. 59-80.

Frost, C.D., and Mailloux, J.M., 2011, Establishing appropriate water quality numeric standards under the Clean Water Act: Lessons from a case study of coalbed methane produced water discharge to the Powder River, Wyoming and Montana, Wyoming Law Review, v. 11, no 1, p 1-23.

Frost, C. D., Pearson, B. N., Ogle, K. M., Heffern, E. L., and Lyman, R. M., 2002, Sr isotopic tracing of aquifer interactions in an area of coal and methane production, Powder River Basin, Wyoming: Geology, v. 30, p. 923–926.

Hanson, B.R., Grattan, S.R., and Fulton, A., 1999, Agricultural salinity and drainage: Davis, California, University of California Irrigation Program, Water Management Handbook Series, Publication 93-01,141 p.

Hoffman, G.J., Rhoades, J. D., Letey, J., Sheng F., 1990, Salinity management, in Hoffman, G.J., Howell, T.A., Solomon, K.H., eds., Management of farm irrigation systems, American Society of Agricultural Engineers, Monograph no. 9, p 667-715.

Horpestad, A., Skaar, D., Dawson, H., 2001, Water Quality Impacts from Coal Bed Methane Development in the Powder River Basin, Wyoming and Montana, Water Quality Technical Report, Montana Department of Environmental Quality website, http://deq.mt.gov/coalbedmethane/cbmreports.mcpx, accessed July 2011.

Jones, N.R., 2008, Geography and geology, in Copeland, D. A., and Ewald, M. L., eds., Water associated with coal beds in Wyoming's Powder River Basin: geology, hydrology, and water quality: Laramie, WY, Wyoming State Geological Survey Exploration Memoir, no. 2, p 45-110.

--------------- 2010, Personal Communication, May 2010.

Love, J. D., and Christiansen, A.C., compilers, 1985, Geologic map of Wyoming: U.S. Geological Survey, 3 sheets, scale 1:500,000.

Mailloux, J.M., Ogle, K., and Frost, C.D., in press, Application of Bayesian model to infer the contribution of coal bed natural gas produced water to the Powder River, Wyoming and Montana: Hydrologic Processes.

McLaughlin, J.F., Frost, C.D., and Sharma, S., 2011, Geochemical analysis of Atlantic Rim water, Carbon County, Wyoming: New applications for characterizing coalbed natural gas reservoirs: American Association of Petroleum Geologists Bulletin, v. 95, no. 2, p. 191-217.

Montana and Wyoming Powder River Interim Water Quality Criteria Memorandum of Cooperation (2002). Montana Board of Environmental Review Amendment of ARM 17.30.670 and 17.30.1202 Pertaining to Nondegradation Requirements for Electrical Conductivity (EC) and Sodium Adsorption Ratio (SAR) (2005). Available at http://aqwatec.mines.edu/produced_water/regs/state/mt/index.htm, accessed September 27, 2010.

Pearson, B. N., 2002, Sr isotope ratio as a monitor of recharge and aquifer communication, Paleocene Fort Union Formation and Eocene Wasatch Formation, Powder River Basin, Wyoming and Montana: Laramie, University of Wyoming, M.S. thesis, 151 p.

Quillinan, S. A., Jones, N.R., DeBruin, R H, and Worman, B., 2010, Coalbed natural gas activity in the Powder River Basin, Wyoming: Wyoming State Geological Survey Map Series-58, scale 1:250,000.

Quillinan, S.A., 2011a, Spatial variability of coalbed natural gas produced water quality, Powder River Basin, Wyoming: Implications for future development, in Quillinan, S.A., 2011, Geochemical and isotopic characterization of water associated with Wyoming's coalbed natural gas development: Laramie, University of Wyoming, M.S. thesis, p.1-48, and 22 figs.

Quillinan, S.A., and Frost, C.D., 2011, Characterization of produced water associated with coalbed natural gas development: a case study of the Powder River Basin, Wyoming, in Quillinan, S.A., 2011, Geochemical and isotopic characterization of water associated with Wyoming's coalbed natural gas development: Laramie, University of Wyoming, M.S. thesis, 49-109 p., and 16 figs.

Quillinan, S.A., 2011b, Isotopic and geochemical characterization of coalbed natural gas produced water of the Atlantic Rim, WY, in Quillinan, S.A., 2011, Geochemical and isotopic characterization of water associated with Wyoming's coalbed natural gas development: Laramie, University of Wyoming, M.S. thesis, 110-145 p., and 9 figs.

Rhoades, J.D.,1982, Reclamation and management of salt-affected soils after drainage in Proc. of the first annual western provincial conf. Rationalization of Water and Soil Research and Management, 123-197. Lethbridge, Alberta, Canada.

Rice, C. A., Ellis, M.S., and Bullock J. H., Jr., 2000, Water coproduced with coalbed methane in the Powder River Basin, Wyoming: Preliminary compositional data: U.S. Geological Survey Open File Report 00-372, 20 p.

Stumm, W., and Morgan, J.J., 1996, Aquatic chemistry: Chemical equilibria and rates in natural waters (3rd ed.): New York, NY, John Wiley and Sons, 1040 p.

Veil, J.A., Puder, M.G., Elcock, D., Redweik, R.J., Jr., 2004. A white paper describing produced water from production of crude oil, natural gas, and coal bed methane. Prepared for U.S. Department of Energy National Energy Technology Laboratory, 79 p., http://www.evs.anl.gov/pub/doc/ProducedWatersWP0401.pdf, accessed September 18, 2010.

Wyoming Department of Environmental Quality, 2005, Water Quality Rules and Regulations, Chapter 8: Quality Standards for Wyoming Groundwaters, 13 p. http://deq.state.wy.us/wqd/WQDrules/Chapter_08.pdf, accessed September 13, 2010.

------------, 2011, Wyoming Department of Environmental Quality CBM Permitting Guideline for Discharges to Irrigated Drainages of the Powder River Basin, http://deq.state.wy.us/wqd/wypdes_permitting/WYPDES_cbm/downloads/WDEQ_CBM_Permitting_Guideline_5-2011.pdf, accessed June 17, 2012.

Wyoming Oil and Gas Conservation Commission, 2012, Coalbed production (1987-2011), http://wogcc.state.wy.us/coalbedchart.cfm, accessed June 2011.

Wyoming Oil and Gas Conservation Commission, 2010.

http://wogcc.state.wy.us/, accessed June, 2011

Wyoming State Geological Survey, 2010, http://www.wsgs.uwyo.edu/, accessed June 2010.

Appendix A: Water Quality Data for CBNG Produced Water, Powder River Basin, Wyoming

Appendix A.

API	Source	Twn	Rng	Long	Lat	Elevation (feet)	Total Depth (feet)	Coal Bed	Coal Zone	pH	TDS (mg/L)	SAR	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	Sr (mg/L)	Ba (mg/L)	Fe (mg/L)	Si (mg/L)	SO_4 (mg/L)	Cl (mg/L)	F (mg/L)	Alkalinity (mg/L)
536103	Campbell et al., 2008	48	76	-105.98243	44.1182	4,656	1,450	Big George	Wyodak Rider	8	1,538	17.7	19	6	342	0.35	0.2	1.4	5.1	<0.01	8.1	1.5	1,190
536109	Campbell et al., 2008	48	76	-105.98817	44.12896	4,665	1,520	Big George	Wyodak Rider	7.9	1,990	15.4	33	13	414	0.5	0.5	0.5	6.4	54.6	11.5	1.4	1,446
539139	Campbell et al., 2008	47	74	-105.69176	44.03341	4,900	1,368	Wyodak	Upper Wyodak	7.3	1,195	--	33	15	227	0.52	0.5	0.1	3.4	0.3	8.7	0.9	897
540399	Campbell et al., 2008	47	74	-105.72188	44.06374	4,957	1,510	Wyodak	Upper Wyodak	7.3	1,578	8.4	42	18	257	0.62	0.7	0.3	2.3	1.9	8.6	0.7	1,037
540415	Campbell et al., 2008	47	74	-105.74111	44.05634	5,054	1,590	Wyodak	Upper Wyodak	7.5	1,214	8.6	37	11	232	0.57	0.5	0.1	2.5	0.1	8.3	0.8	915
540418	Campbell et al., 2008	47	74	-105.73102	44.05693	5,032	1,584	Wyodak	Upper Wyodak	7.3	1,266	8.3	44	13	243	0.61	0.5	0.1	3.1	0.2	31.7	0.5	1,013
541776	Campbell et al., 2008	46	74	-105.6924	43.9749	5,011	1,175	Big George	Wyodak Rider	7.7	1,349	11.5	24	12	278	0.50	0.3	0.1	3.2	1.7	7.5	1.0	1,016
541784	Campbell et al., 2008	47	74	-105.6925	44.0117	5,013	1,091	Big George	Wyodak Rider	7.7	1,109	10.4	26	7	232	0.48	0.4	0.1	1.5	2	5.7	0.7	1,013
541788	Campbell et al., 2008	47	74	-105.7022	44.0115	5,000	1,077	Big George	Wyodak Rider	7.6	1,343	9.5	31	16	262	0.59	0.7	0.1	2.4	<0.05	6.9	0.8	952
541789	Campbell et al., 2008	47	74	-105.7069	44.0006	5,026	1,168	Big George	Wyodak Rider	7.6	1,262	7.9	38	17	232	0.60	0.6	0.1	2.9	2.5	7.0	0.8	1,062
541935	Campbell et al., 2008	46	74	-105.6972	43.9859	5,019	1,164	Big George	Wyodak Rider	7.8	1,402	11.0	26	14	279	0.55	0.4	0.1	4.4	1.4	6.5	0.9	1,063
541938	Campbell et al., 2008	46	74	-105.69671	43.99362	4,980	1,080	Big George	Wyodak Rider	7.5	1,284	11.3	25	10	267	0.52	0.4	0.1	3.7	6.9	6.6	0.6	956
542226	Campbell et al., 2008	47	73	-105.68270	44.03750	4,889	1,325	Wyodak	Upper Wyodak	7.7	883	8.1	21	9	176	0.31	0.4	0.0	0.1	0.1	9.3	1.0	1,031
543933	Campbell et al., 2008	46	74	-105.73195	43.96693	4,995	1,230	Big George	Wyodak Rider	7.3	1,378	11.7	25	12	286	0.55	0.4	0.1	5.1	0.5	9.3	0.9	1,029
543939	Campbell et al., 2008	46	74	-105.74197	43.96745	2,016	1,308	Big George	Wyodak Rider	7.7	1,407	12.3	20	14	292	0.43	0.4	0.3	4.0	1.2	9.1	1.5	1,054
543943	Campbell et al., 2008	46	74	-105.70165	43.93814	5,039	1,070	Big George	Wyodak Rider	7.6	1,192	11.9	23	7	252	0.49	0.3	0.6	2.5	1.6	9.2	0.7	890
543944	Campbell et al., 2008	46	74	-105.71654	43.92713	4,894	1,010	Big George	Wyodak Rider	7.3	1,201	11.9	21	9	258	0.46	0.4	0.1	3.8	9.8	9.1	0.8	887
543946	Campbell et al., 2008	46	74	-105.71678	43.92720	4,894	1,365	Wyodak	Upper Wyodak	7.9	1,046	10.6	21	7	219	0.30	0.2	0.0	2.1	0.1	10.2	0.6	873
543952	Campbell et al., 2008	46	74	-105.72148	43.94537	4,963	1,085	Big George	Wyodak Rider	8.1	1,186	12.0	20	9	256	0.40	0.2	0.1	3.0	2.9	15.3	0.8	87

Appendix A.

API	Source	Twn	Rng	Long	Lat	Elevation (feet)	Total Depth (feet)	Coal Bed	Coal Zone	pH	TDS (mg/L)	SAR	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	Sr (mg/L)	Ba (mg/L)	Fe (mg/L)	Si (mg/L)	SO_4 (mg/L)	Cl (mg/L)	F (mg/L)	Alkalinity (mg/L)
543957	Campbell et al., 2008	46	74	-105.7172	43.96395	5,044	1,225	Big George	Wyodak Rider	7.3	1,361	11.0	32	11	282	0.70	0.6	0.1	5.1	2.3	9.4	0.7	1,010
543959	Campbell et al., 2008	46	74	-105.71744	43.93495	4,938	1,080	Big George	Wyodak Rider	7.5	1,215	11.7	22	9	256	0.43	0.3	0.1	3.1	2.0	8.0	0.8	908
543969	Campbell et al., 2008	46	74	-105.6973	43.94207	4,955	975	Big George	Wyodak Rider	7.4	1,306	10.3	34	9	262	--	0.5	0.1	4.7	--	8.0	0.6	982
543981	Campbell et al., 2008	46	74	-105.70715	43.9564	4,996	1,122	Big George	Wyodak Rider	7.4	1,330	10.4	33	10	266	0.72	0.5	0.1	4.9	0.3	8.6	0.6	998
547297	Campbell et al., 2008	46	72	-105.545	43.92083	4,797	1,028	Canyon	Lower Wyodak	7.5	997	7.8	21	16	195	0.38	0.4	0.1	2.1	0.8	11.2	1.3	738
550056	Campbell et al., 2008	48	76	-105.98385	44.13289	4,700	1,609	Big George	Wyodak Rider	7.4	1,504	7.8	57	19	264	1.32	0.5	9.5	7.1	<0.01	5.3	1.5	1,172
554969	Campbell et al., 2008	52	75	-105.8624	44.49536	4,056	720	Canyon	Lower Wyodak	8.3	1,029	11.9	16	6	220	0.22	0.3	0.0	5.4	1.9	9.3	0.8	763
554972	Campbell et al., 2008	52	75	-105.84142	44.4957	4,075	1,725	Wall	Wall	8.2	1,617	12.6	37	11	336	0.58	1.0	0.1	7.1	3.9	17.3	0.9	1,190
554973	Campbell et al., 2008	52	75	-105.86244	44.49523	4,055	1,460	Wall	Wall	8.3	1,489	15.3	21	9	331	0.33	1.0	0.1	7.5	0.9	24.1	1.0	1,080
554976	Campbell et al., 2008	52	75	-105.83723	44.49898	4,145	589	Lower Anderson	Upper Wyodak	8.5	1,642	16.4	26	7	365	0.42	0.3	0.2	4	5.8	20.7	0.9	1,208
554978	Campbell et al., 2008	52	75	-105.86236	44.4955	4,059	508	Lower Anderson	Upper Wyodak	8.6	1,445	18.6	11	8	329	0.32	0.2	0.0	4.1	0.6	12.4	0.8	1,074
1922921	Campbell et al., 2008	47	77	-106.09705	44.0192	4,315	1,561	Big George	Wyodak Rider	7.8	3,631	31.7	21	16	796	0.08	0.9	0.4	6.2	<0.01	31.3	2.3	2,715
1923370	Campbell et al., 2008	42	77	-106.07102	43.61728	4,794	1,235	Big George	Wyodak Rider	7.9	1,193	6.0	37	23	189	0.41	0.9	0.6	5.4	<0.01	7.3	1.0	2,227
1923392	Campbell et al., 2008	42	77	-106.08609	43.62815	4,952	1,330	Big George	Wyodak Rider	8.1	1,351	8.2	36	18	238	0.77	0.8	0.6	5.6	<0.01	8.7	0.7	2,166
1923393	Campbell et al., 2008	42	77	-106.08046	43.63135	4,940	1,462	Big George	Wyodak Rider	8.1	1,348	5.7	41	32	201	0.47	1.1	2.3	5.6	<0.01	7.7	1.0	2,514
1923394	Campbell et al., 2008	42	77	-106.08064	43.62442	4,921	1,332	Big George	Wyodak Rider	8.0	1,662	7.1	48	36	266	0.63	1.1	0.8	5.5	0.2	8.4	1.0	2,929
1923400	Campbell et al., 2008	42	77	-106.07086	43.6245	4,839	1,322	Big George	Wyodak Rider	7.8	1,266	6.4	34	26	204	0.49	1.4	0.5	5.4	<0.01	8.0	1.0	2,081
1924064	Campbell et al., 2008	48	77	-106.15857	44.12209	4,131	1,451	Big George	Wyodak Rider	7.7	3,823	27.7	39	18	831	0.11	0.8	0.7	6.1	<0.01	35.9	2.3	2,856
1924199	Campbell et al., 2008	43	77	-106.10314	43.67571	4,769	1,583	Big George	Wyodak Rider	8.1	2,010	8.2	51	39	320	1.41	2.6	0.9	8.7	<0.01	8.6	1.2	3,136

Appendix A.

API	Source	Twn	Rng	Long	Lat	Elevation (feet)	Total Depth (feet)	Coal Bed	Coal Zone	pH	TDS (mg/L)	SAR	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	Sr (mg/L)	Ba (mg/L)	Fe (mg/L)	Si (mg/L)	SO_4 (mg/L)	Cl (mg/L)	F (mg/L)	Alkalinity (mg/L)
1924888	Campbell et al., 2008	43	77	-106.13644	43.69223	4,645	1,489	Big George	Wyodak Rider	7.8	3,033	12.1	57	52	526	0.16	1.4	1.0	6.2	0.1	10.7	1.9	3,484
1924891	Campbell et al., 2008	43	77	-106.11151	43.70341	4,667	1,443	Big George	Wyodak Rider	7.9	4,467	21.2	60	44	884	0.50	1.2	1.1	5.2	0.1	10.5	2.6	3,631
1924897	Campbell et al., 2008	43	77	-106.12528	43.69961	4,598	1,604	Big George	Wyodak Rider	8	1,844	9.4	38	31	320	0.07	0.7	0.6	5.9	0.1	7.7	1.3	2,294
1924914	Campbell et al., 2008	43	77	-106.1416	43.68881	4,653	1,536	Big George	Wyodak Rider	8.1	1,419	8.7	26	22	249	0.07	1.4	0.4	6.2	0.1	7.1	1.2	1,599
1925029	Campbell et al., 2008	43	77	-106.11674	43.67101	4,836	1,607	Big George	Wyodak Rider	7.9	1,144	6.2	29	23	185	0.15	0.7	0.4	5.9	<0.01	6.1	1.1	1,745
1925038	Campbell et al., 2008	42	77	-106.09629	43.61363	5,015	1,438	Big George	Wyodak Rider	8.1	1,690	9.6	30	25	292	0.38	1.1	0.5	5.8	<0.01	10.3	1.2	1,806
1925050	Campbell et al., 2008	43	77	-106.11559	43.64951	4,873	1,450	Big George	Wyodak Rider	8.2	2,263	12.1	52	25	425	0.81	1.1	0.9	5.5	<0.01	10.4	1.4	3,179
1925054	Campbell et al., 2008	43	77	-106.1076	43.64996	4,896	1,604	Big George	Wyodak Rider	8.1	912	6.4	19	16	155	0.13	0.6	0.3	5.9	<0.01	6	1.0	1,141
1925061	Campbell et al., 2008	42	77	-106.13576	43.63462	4,898	1,434	Big George	Wyodak Rider	8.2	2,334	10.4	39	44	401	0.20	1.2	0.7	5.9	<0.01	13.1	1.4	2,380
1925073	Campbell et al., 2008	42	77	-106.13616	43.6426	4,875	1,485	Big George	Wyodak Rider	8.3	3,170	14.9	42	48	596	0.22	1.5	0.7	6.0	<0.01	18.8	1.9	2,569
1925080	Campbell et al., 2008	42	77	-106.13067	43.63933	4,906	1,490	Big George	Wyodak Rider	8.3	4,020	30.9	25	23	887	0.13	0.7	0.5	6.2	<0.01	38.6	2.5	1,519
1925086	Campbell et al., 2008	42	77	-106.0966	43.64328	4,983	1,479	Big George	Wyodak Rider	8.4	1,364	7.4	29	27	230	0.23	0.8	0.4	5.5	<0.01	8.8	1.1	1,794
1925087	Campbell et al., 2008	42	77	-106.10098	43.63931	4,921	1,493	Big George	Wyodak Rider	7.9	1,012	8.4	14	14	186	0.19	0.7	0.2	5.7	<0.01	5.8	0.9	842
1925088	Campbell et al., 2008	42	77	-106.10142	43.6467	4,908	1,517	Big George	Wyodak Rider	7.9	2,160	9.7	58	33	373	0.78	1.3	0.9	5.8	0.1	10.4	1.2	3,564
1925099	Campbell et al., 2008	42	77	-106.14635	43.64266	4,911	1,484	Big George	Wyodak Rider	8.0	3,161	12.6	52	57	550	0.17	1.5	0.9	6.2	<0.01	19.3	1.9	3,155
1925501	Campbell et al., 2008	48	76	-106.04722	44.10518	4,282	1,205	Big George	Wyodak Rider	8.3	2,699	21.8	29	15	582	0.78	0.9	0.5	5.9	0.2	18.8	1.9	2,032
1925517	Campbell et al., 2008	48	76	-106.04768	44.12052	4,414	1,268	Big George	Wyodak Rider	8.2	3,195	31.0	23	12	726	0.85	1.0	0.4	6.2	0.1	22.6	2.2	2,392
1925557	Campbell et al., 2008	48	77	-106.06715	44.10619	4,264	1,179	Big George	Wyodak Rider	8.1	3,795	29.6	33	17	832	1.64	2.3	0.6	6	<0.01	24.2	2.4	2,850
1925566	Campbell et al., 2008	48	77	-106.06255	44.13225	4,363	1,327	Big George	Wyodak Rider	7.9	3,416	25.6	30	20	732	0.76	0.8	0.5	6.7	0.2	32.5	2.3	2,575

Appendix A.

API	Source	Twn	Rng	Long	Lat	Elevation (feet)	Total Depth (feet)	Coal Bed	Coal Zone	pH	TDS (mg/L)	SAR	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	Sr (mg/L)	Ba (mg/L)	Fe (mg/L)	Si (mg/L)	SO_4 (mg/L)	Cl (mg/L)	F (mg/L)	Alkalinity (mg/L)
1925568	Campbell et al., 2008	48	77	-106.06297	44.13853	4,476	1,539	Big George	Wyodak Rider	7.7	3,270	24.8	31	18	700	0.56	0.7	0.5	6.3	0.1	25.5	2.2	2,471
1926313	Campbell et al., 2008	43	77	-106.13639	43.67129	4,742	1,553	Big George	Wyodak Rider	8.3	1,175	7.2	23	21	199	0.09	0.7	0.4	5.9	<0.01	6.9	1.2	1,373
1926349	Campbell et al., 2008	52	77	-106.15334	44.46929	3,887	1,577	Cook	Cook	8.3	1,757	18.3	17	9	378	0.37	0.9	0.1	8.2	1.9	28.9	1.3	1,300
1926350	Campbell et al., 2008	52	77	-106.15327	44.46916	3,883	1,202	Anderson	Upper Wyodak	8.5	3,046	35.4	14	9	688	0.23	0.6	0.1	7	2.3	26.4	1.8	2,288
1926351	Campbell et al., 2008	52	77	-106.14548	44.46963	3,793	1,075	Anderson	Upper Wyodak	8.3	2,343	36.3	8	5	528	0.15	0.3	0.1	5.9	1.8	21.6	1.7	1,763
1926352	Campbell et al., 2008	52	77	-106.14842	44.46557	3,778	1,060	Anderson	Upper Wyodak	8.6	2,362	52.5	3	5	636	0.13	0.1	--	3.3	--	21.5	1.6	1,684
1926353	Campbell et al., 2008	52	77	-106.14832	44.47305	3,843	1,200	Anderson	Upper Wyodak	8.4	2,609	33.1	12	7	584	0.23	0.5	0.1	7	0.4	24.3	1.7	1,965
1926354	Campbell et al., 2008	52	77	-106.14567	44.46939	3,795	1,649	Wall	Wall	9.2	1,123	16.0	6	8	255	0.21	0.1	0.0	0.2	14.1	21.3	0.8	805
1926357	Campbell et al., 2008	52	77	-106.14830	44.47291	3,842	1,515	Cook	Cook	8.4	2,714	37.6	11	6	632	0.26	0.4	0.2	6.7	0.3	32.5	1.9	2,014
1926358	Campbell et al., 2008	52	77	-106.14829	44.46568	3,777	1,451	Cook	Cook	8.3	1,841	19.1	18	10	404	0.37	1.0	0.1	7.7	<.05	26.1	1.2	1,361
1926359	Campbell et al., 2008	52	77	-106.14558	44.46951	3,794	1,455	Cook	Cook	8.3	2,544	26.8	19	10	579	0.49	0.8	0.1	6.9	1.1	32.6	1.6	1,879
530473	Frost et al., 2002	48	72	-105.49189	44.13232	4,613	565	Wyodak	Upper Wyodak	7.5	382	6.0	15	9	120	0.30	--	--	9.9	0.1	8.9	1.6	422
530802	Frost et al., 2002	46	71	-105.40543	43.98739	4,625	340	Wyodak	Upper Wyodak	8	644	8.0	32	14	210	0.61	--	--	9.1	0.1	15	1.4	712
530994	Frost et al., 2002	47	71	-105.42537	44.02742	4,709	399	Wyodak	Upper Wyodak	8	625	7.0	37	15	200	0.68	--	--	9.7	0.1	12	1.1	699
531229	Frost et al., 2002	50	72	-105.49620	44.31517	4,443	270	Wyodak	Upper Wyodak	7.4	720	8.4	32	18	240	0.7	0.5	0.3	4.1	0.1	9.5	1.0	810
531234	Frost et al., 2002	45	71	-105.41238	43.86675	4,837	457	Wyodak	Upper Wyodak	7.3	660	6.3	50	18	200	1.00	1.0	0.6	4.3	<0.01	12	0.8	720
531384	Frost et al., 2002	45	72	-105.49349	43.90293	4,864	722	Anderson	Upper Wyodak	--	571	7.0	--	15	190	1.5	--	--	--	0.1	24	--	615
531494	Frost et al., 2002	45	72	-105.46752	43.89283	4,813	570	Anderson	Upper Wyodak	7.3	608	6.9	17	9	140	0.4	0.3	0.2	4.9	0.0	12	1.1	450
531760	Frost et al., 2002	45	72	-105.51407	43.86921	4,808	715	Anderson	Upper Wyodak	7.2	510	7.3	23	11	170	0.52	0.5	0.3	4.8	0.0	17	0.7	570

Appendix A.

API	Source	Twn	Rng	Long	Lat	Elevation (feet)	Total Depth (feet)	Coal Bed	Coal Zone	pH	TDS (mg/L)	SAR	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	Sr (mg/L)	Ba (mg/L)	Fe (mg/L)	Si (mg/L)	SO_4 (mg/L)	Cl (mg/L)	F (mg/L)	Alkalinity (mg/L)
531760	Frost et al., 2002	45	72	-105.51407	43.86921	4,808	715	Anderson	Upper Wyodak	7.2	573	10.5	23	11	170	0.52	0.5	0.3	4.8	0.0	17	0.7	570
532140	Frost et al., 2002	43	72	-105.44471	43.71432	4,861	675	Wyodak	Upper Wyodak	7.3	396	6.0	17	8	130	0.36	--	--	10	1.8	9.3	1.2	433
533115	Frost et al., 2002	45	72	-105.46381	43.83005	4,795	746	Wyodak	Upper Wyodak	7.1	390	6.1	19	10	130	0.4	0.4	0.3	4.5	0.8	9.2	1.2	420
533964	Frost et al., 2002	49	71	-105.43045	44.20856	4,672	450	Anderson	Upper Wyodak	7.2	620	7.1	36	14	200	0.66	0.6	0.2	3.8	4.0	10.0	1.1	690
533977	Frost et al., 2002	48	73	-105.61105	44.10691	4,836	1,066	Wyodak	Upper Wyodak	7.8	697	7.0	36	23	210	0.77	--	--	11	0.9	9.1	1.3	789
534071	Frost et al., 2002	46	71	-105.42066	43.92573	4,665	397	Wyodak	Upper Wyodak	7.1	509	--	25	11	159	0.57	--	0.4	3.6	0.3	14.2	1.0	583
534083	Frost et al., 2002	47	73	-105.61156	44.08138	4,746	992	Wyodak	Upper Wyodak	7.2	710	7.0	37	24	220	0.75	--	0.6	5.1	1.9	14.0	1.3	800
534171	Frost et al., 2002	45	74	-105.73106	43.88351	5,046	1,432	Canyon	Lower Wyodak	7.3	900	9.3	52	16	300	1	0.6	0.8	5.3	12	9.2	0.8	1,000
534249	Frost et al., 2002	48	73	-105.62092	44.10389	4,900	775	Wyodak	Upper Wyodak	7.7	680	6.0	40	22	210	0.82	--	--	11	0.1	8.5	1.2	771
534524	Frost et al., 2002	44	71	-105.39960	43.74680	4,798	620	Wyodak	Upper Wyodak	7.1	494	--	28	12	152	0.58	--	0.6	4.3	--	6.0	1.1	576
535359	Frost et al., 2002	46	73	-105.58056	43.96752	4,783	1,044	Wyodak	Upper Wyodak	6.9	777	--	49	22	231	1.00	--	0.7	5.0	0.0	7.3	1.2	910
535416	Frost et al., 2002	51	74	-105.75997	44.36711	4,363	812	Anderson	Upper Wyodak	7.5	540	13.0	14	5	220	0.25	0.2	0.0	5.8	0.8	12.0	0.8	580
535851	Frost et al., 2002	51	74	-105.79895	44.36625	4,344	963	Anderson	Upper Wyodak	7.7	1,306	--	47	22	465	1.15	--	2.3	5.0	1.2	8.3	0.6	1,507
536791	Frost et al., 2002	46	73	-105.67129	43.98233	4,932	1,008	Big George	Wyodak Rider	7.3	772	--	36	11	268	1.04	--	1.9	4.5	0.0	7.8	0.6	888
539435	Frost et al., 2002	45	73	-105.60111	43.84389	4,870	1,040	Wyodak	Upper Wyodak	7	810	7.1	59	19	250	1.2	0.8	0.8	5.1	1.8	7.1	0.9	930
529839	Pearson, 2002	51	72	-105.55084	44.36848	4,330	480	Wyodak	Upper Wyodak	6.8	990	7.7	57	36	300	1.3	1.0	0.7	4.2	0.8	8.9	1.0	1,130
530949	Pearson, 2002	47	72	-105.47708	44.04820	4,651	612	Wyodak	Upper Wyodak	7.2	530	7.0	26	12	170	0.52	--	0.3	4.2	<0.01	12.0	1.1	600
531900	Pearson, 2002	47	72	-105.56042	44.05848	4,718	853	Wyodak	Upper Wyodak	6.9	620	6.9	33	19	200	0.65	0.7	0.4	4.7	0.7	9.0	1.1	680
531934	Pearson, 2002	48	73	-105.58881	44.17130	4,718	842	Wyodak	Upper Wyodak	7.7	888	8.0	49	27	270	1.00	--	--	10	0.1	7.7	0.8	1,040

Appendix A.

API	Source	Twn	Rng	Long	Lat	Elevation (feet)	Total Depth (feet)	Coal Bed	Coal Zone	pH	TDS (mg/L)	SAR	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	Sr (mg/L)	Ba (mg/L)	Fe (mg/L)	Si (mg/L)	SO_4 (mg/L)	Cl (mg/L)	F (mg/L)	Alkalinity (mg/L)
532860	Pearson, 2002	44	72	-105.44485	43.80146	4,927	879	Wyodak	Upper Wyodak	7.1	480	6.1	27	11	150	0.56	0.5	1.7	4.4	0.8	10.0	1.0	550
532869	Pearson, 2002	52	73	-105.63306	44.5218	4,092	528	Canyon	Lower Wyodak	7.2	894	--	--	--	--	--	--	--	--	0.2	8.9	--	1,235
532910	Pearson, 2002	48	73	-105.60496	44.13226	4,712	901	Wyodak	Upper Wyodak	7	840	8.1	42	25	270	0.95	1.3	0.8	4.6	<0.01	9.5	0.8	950
533031	Pearson, 2002	49	72	-105.48659	44.21950	4,637	531	Anderson	Upper Wyodak	--	800	6.9	--	--	--	--	--	--	--	--	--	--	--
533187	Pearson, 2002	43	71	-105.43550	43.72163	4,901	606	Wyodak	Upper Wyodak	7.1	470	5.7	32	13	150	0.56	0.2	0.6	5.3	17	10.0	1.6	490
533307	Pearson, 2002	48	75	-105.82190	44.09837	4,643	1,094	Big George	Wyodak Rider	--	900	--	--	--	--	--	--	--	--	4.3	7.9	--	1,041
533975	Pearson, 2002	48	73	-105.60644	44.08870	4,765	1,014	Wyodak	Upper Wyodak	7	660	7.3	34	18	210	0.71	--	4.9	4.8	<0.01	8.6	0.7	760
534118	Pearson, 2002	47	73	-105.64655	44.00868	4,925	1,315	Wyodak	Upper Wyodak	7.1	700	7.8	41	15	230	0.85	--	3.8	5.2	0.9	9.4	1.0	800
534174	Pearson, 2002	45	74	-105.73128	43.88731	5,062	1,225	Anderson	Upper Wyodak	7.4	970	11.0	38	18	340	1.2	0.8	0.5	4.7	5.1	48.0	0.6	1,020
534176	Pearson, 2002	45	74	-105.73625	43.88350	5,030	1,146	Anderson	Upper Wyodak	7.3	1,120	12.0	56	18	390	1.8	0.8	1.1	4.6	1.5	60.0	0.5	1,170
534205	Pearson, 2002	55	73	-105.59760	44.74827	3,971	563	Cook-Canyon	Multiple	7.6	800	11.0	30	14	290	0.45	0.5	0.4	3.7	3	10	0.7	880
534424	Pearson, 2002	56	75	-105.85410	44.78217	4,044	543	Canyon	Lower Wyodak	7.6	1,320	23.0	19	14	540	0.29	0.5	0.0	5.1	1.2	13	0.6	1,440
534425	Pearson, 2002	55	75	-105.85347	44.77882	4,030	805	Lower Canyon	Lower Wyodak	7.4	1,600	23.0	26	19	640	0.53	0.7	0.2	4.7	1.6	6.7	0.9	1,810
534475	Pearson, 2002	56	75	-105.90096	44.80021	4,077	645	Canyon	Lower Wyodak	7.6	1,550	22.0	27	18	610	0.42	0.6	0.8	4.8	0.9	7.7	0.5	1,760
534517	Pearson, 2002	42	75	-105.80743	43.56701	5,314	1,075	Big George	Wyodak Rider	7.2	649	--	--	--	--	--	--	--	--	3.0	7.9	--	748
534690	Pearson, 2002	56	75	-105.8329	44.7865	3,961	711	Lower Canyon	Lower Wyodak	7.4	1,050	22.0	15	8	430	0.26	0.4	0.3	4.7	0.2	11	0.6	1,160
535333	Pearson, 2002	56	75	-105.83851	44.79031	3,956	761	Anderson-Lower Anderson	Multiple	7.6	1,390	18.0	35	19	530	0.69	0.6	0.3	4.6	1.9	6.4	0.4	1,570
535352	Pearson, 2002	56	76	-105.94594	44.82513	4,157	1,020	Lower Cook	Cook	7.5	2,000	32.0	24	15	800	0.33	0.8	0.6	5.1	0.2	14	1.0	2,260
535476	Pearson, 2002	43	74	-105.68806	43.735	5,008	925	Big George	Wyodak Rider	--	671	--	--	--	--	--	--	--	--	0.1	8.6	--	796

Appendix A.

API	Source	Twn	Rng	Long	Lat	Elevation (feet)	Total Depth (feet)	Coal Bed	Coal Zone	pH	TDS (mg/L)	SAR	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	Sr (mg/L)	Ba (mg/L)	Fe (mg/L)	Si (mg/L)	SO_4 (mg/L)	Cl (mg/L)	F (mg/L)	Alkalinity (mg/L)
536006	Pearson, 2002	56	75	-105.89528	44.80392	4,038	991	Wall	Wall	7.5	1,550	32.0	15	9	630	0.27	0.3	0.6	5.6	0.1	18	1.4	1,740
536125	Pearson, 2002	49	72	-105.50685	44.25615	4,553	498	Anderson	Upper Wyodak	7.3	770	7.6	44	24	250	0.95	0.7	0.4	3.9	0.1	11	1.0	850
537482	Pearson, 2002	49	72	-105.55708	44.18918	4,888	911	Anderson	Upper Wyodak	7.1	800	8.0	46	22	260	0.94	0.9	0.8	4.6	0.1	9	0.8	900
538294	Pearson, 2002	55	75	-105.90094	44.73838	3,980	603	Canyon Rider	Lower Wyodak	7.7	1,331	--	--	--	--	--	--	--	--	0.8	8.1	--	1,602
538300	Pearson, 2002	55	75	-105.89102	44.74568	3,805	775	Wall-Lower Canyon	Multiple	7.6	1,350	--	--	--	--	--	--	--	--	1.2	14.8	--	1,586
538804	Pearson, 2002	48	75	-105.82186	44.09840	4,644	1,375	Wyodak	Upper Wyodak	7.2	897	--	--	--	--	--	--	--	--	3.3	7.5	--	--
539087	Pearson, 2002	47	74	-105.72742	44.03015	4,996	1,514	Big George-Wyodak	Multiple	8.0	907	--	55	19	282	--	0.1	1.8	--	<0.01	5.6	0.9	1,040
540220	Pearson, 2002	52	73	-105.63277	44.52166	4,099	811	Wall	Wall	7.3	593	--	--	--	--	--	--	--	--	0.0	8.7	--	732
540502	Pearson, 2002	56	75	-105.90022	44.82957	3,807	360	Canyon Rider	Lower Wyodak	7.5	1,443	--	--	--	--	--	--	--	--	0.5	6.8	--	1,711
540518	Pearson, 2002	56	75	-105.90021	44.82961	3,807	615	Cook	Cook	7.7	1,362	--	--	--	--	--	--	--	--	0.6	12.1	--	1,575
540534	Pearson, 2002	56	75	-105.90020	44.82965	3,807	701	Wall	Wall	7.7	1,624	--	--	--	--	--	--	--	--	1.1	16.2	--	1,882
541229	Pearson, 2002	53	74	-105.77539	44.6044	4,356	1,120	Cook	Cook	7.2	1,004	--	--	--	--	--	--	--	--	0.3	10.8	--	1,192
541364	Pearson, 2002	48	76	-105.9828	44.1402	4,656	1,688	Big George	Wyodak Rider	7.2	1,308	--	35	20	507	0.93	--	7.1	6.5	2.3	15.5	--	1,436
542974	Pearson, 2002	53	73	-105.67904	44.6091	4,183	492	Canyon	Lower Wyodak	7.8	715	--	21	9	279	0.45	--	0.5	4.0	6.3	11.1	0.8	764
543698	Pearson, 2002	43	73	-105.63694	43.73472	5,107	900	Big George	Wyodak Rider	--	571	--	--	--	--	0.71	--	--	--	0.3	10.4	--	650
1921141	Pearson, 2002	47	77	-106.05129	44.00230	4,338	1,241	Big George	Wyodak Rider	--	1,717	--	--	--	--	--	--	--	--	--	10	--	2,070
1921469	Pearson, 2002	49	76	-106.05439	44.21128	4,049	1,043	Big George	Wyodak Rider	7.3	1,418	--	--	--	--	--	--	--	--	17.8	127	1.8	1,441
1921558	Pearson, 2002	53	77	-106.10772	44.54545	3,820	1,667	Wall	Wall	7.1	1,549	--	--	--	--	--	--	--	--	0.0	14.7	1.0	1,766
1921910	Pearson, 2002	53	77	-106.10758	44.55631	3,908	978	Anderson	Upper Wyodak	7.4	1,698	--	--	--	--	--	--	--	--	1.6	18.1	0.8	1,973

Appendix A.

API	Source	Twn	Rng	Long	Lat	Elevation (feet)	Total Depth (feet)	Coal Bed	Coal Zone	pH	TDS (mg/L)	SAR	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	Sr (mg/L)	Ba (mg/L)	Fe (mg/L)	Si (mg/L)	SO_4 (mg/L)	Cl (mg/L)	F (mg/L)	Alkalinity (mg/L)
3320335	Pearson, 2002	54	76	-106.02277	44.62621	3,811	656	Anderson	Upper Wyodak	7.7	1,240	24.0	19	9	500	0.38	0.4	0.2	4.7	0.1	11	0.5	1,380
3320688	Pearson, 2002	58	83	-106.83521	44.95824	3,579	442	Anderson	Upper Wyodak	7.8	1,289	--	5	2	539	0.36	--	--	6.0	0.7	4.5	2.1	1,463
3320827	Pearson, 2002	57	83	-106.86071	44.93943	3,531	660	Anderson	Upper Wyodak	7.7	1,284	--	4	2	537	0.26	--	--	22	0.0	5	1.6	1,428
3321101	Pearson, 2002	54	77	-106.14896	44.62129	3,921	917	Anderson	Upper Wyodak	7.9	1,446	--	15	7	591	0.31	--	0.5	4.7	1.6	15.1	--	1,619
3321346	Pearson, 2002	53	77	-106.1042	44.60365	3,811	904	Anderson	Upper Wyodak	7.5	1,741	--	30	14	705	0.73	--	0.8	4.8	0.9	22.8	1.0	1,918
530248	WDEQ	45	71	-105.37144	43.89678	4,812	450	Canyon	Lower Wyodak	--	934	6.7	37	14	230	--	--	--	--	--	13	--	640
531129	WDEQ	46	72	-105.46561	43.99446	4,750	619	Wyodak	Upper Wyodak	--	693	6.8	24	12	170	--	--	--	--	--	13	--	474
531232	WDEQ	45	72	-105.45792	43.85611	4,731	665	Wyodak	Upper Wyodak	--	502	7.9	17	7	129	--	--	--	--	--	14	--	335
531341	WDEQ	45	72	-105.48753	43.90704	4,743	515	Anderson	Upper Wyodak	--	742	6.4	24	16	185	--	--	--	--	2	25	--	490
531453	WDEQ	45	72	-105.45816	43.86333	4,755	740	Wyodak	Upper Wyodak	--	590	8.0	20	8	152	--	--	--	--	--	15	--	395
531946	WDEQ	43	73	-105.67153	43.73155	4,989	758	Big George	Wyodak Rider	--	1,294	6.1	66	14	314	--	--	--	--	6	11	--	883
532031	WDEQ	46	71	-105.43559	43.97282	4,624	355	Wyodak	Upper Wyodak	--	802	7.1	32	12	210	--	--	--	--	--	18	--	530
532066	WDEQ	48	72	-105.55359	44.09530	4,617	860	Wyodak	Upper Wyodak	--	700	5.9	24	15	164	--	--	--	--	--	9	--	488
532690	WDEQ	54	73	-105.67844	44.63462	4,071	459	Lower Canyon	Lower Wyodak	--	1,322	8.8	35	20	342	--	--	--	--	--	8	--	917
532844	WDEQ	46	74	-105.70142	43.91626	4,865	873	Big George	Wyodak Rider	--	1,182	7.7	46	13	296	--	--	--	--	2	10	--	815
532880	WDEQ	49	73	-105.62887	44.19639	4,798	989	Wyodak	Upper Wyodak	--	1,269	6.5	40	28	320	--	--	--	--	--	11	--	870
533076	WDEQ	49	72	-105.49625	44.18626	4,744	653	Wyodak	Upper Wyodak	--	810	6.6	28	14	192	--	--	--	--	3	9	--	564
533248	WDEQ	54	73	-105.67841	44.63824	4,157	555	Lower Canyon	Lower Wyodak	--	1,028	8.8	27	14	254	--	--	--	--	3	10	--	720
533287	WDEQ	48	73	-105.62980	44.16787	4,812	1,002	Wyodak	Upper Wyodak	--	1,156	6.1	38	24	270	--	--	--	--	--	11	--	813

Appendix A.

API	Source	Twn	Rng	Long	Lat	Elevation (feet)	Total Depth (feet)	Coal Bed	Coal Zone	pH	TDS (mg/L)	SAR	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	Sr (mg/L)	Ba (mg/L)	Fe (mg/L)	Si (mg/L)	SO_4 (mg/L)	Cl (mg/L)	F (mg/L)	Alkalinity (mg/L)
533313	WDEQ	48	72	-105.52734	44.12474	4,644	700	Wyodak	Upper Wyodak	--	441	8.8	13	6	115	--	--	--	--	--	12	--	295
533402	WDEQ	44	74	-105.69253	43.74924	4,980	850	Big George	Wyodak Rider	--	926	7.3	39	10	231	--	--	--	--	4	12	--	630
533461	WDEQ	43	73	-105.65799	43.71700	4,994	815	Big George	Wyodak Rider	--	1,312	5.6	74	16	324	--	--	--	--	--	18	--	880
533647	WDEQ	54	72	-105.57111	44.64570	4,237	258	Anderson	Upper Wyodak	--	1,010	5.6	33	18	202	--	--	--	--	2	9	--	746
534189	WDEQ	51	73	-105.59872	44.35712	4,430	625	Canyon	Lower Wyodak	--	1,611	3.9	66	49	329	--	--	--	--	--	7	--	1,160
534331	WDEQ	46	71	-105.35951	43.95884	4,655	322	Wyodak	Upper Wyodak	--	1,081	6.3	42	17	252	--	--	--	--	--	13	--	757
534414	WDEQ	42	76	-105.94467	43.56263	5,285	1,364	Anderson	Upper Wyodak	--	1,268	2.9	73	44	242	--	--	--	--	--	6	--	903
534433	WDEQ	42	75	-105.84313	43.57358	5,327	1,180	Anderson	Upper Wyodak	--	1,036	4.7	66	15	243	--	--	--	--	--	12	--	700
534486	WDEQ	43	71	-105.40520	43.73250	4,808	628	Wyodak	Upper Wyodak	--	487	5.4	21	9	111	--	--	--	--	--	7	--	339
534491	WDEQ	48	73	-105.66083	44.14389	4,795	1,103	Wyodak	Upper Wyodak	--	1,206	6.5	36	25	290	--	--	--	--	--	10	--	845
534790	WDEQ	53	73	-105.62840	44.55122	4,054	296	Canyon	Lower Wyodak	--	1,187	5.7	44	22	262	--	--	--	--	--	11	--	848
534874	WDEQ	43	71	-105.36411	43.69214	4,783	531	Wyodak	Upper Wyodak	--	480	6.1	18	9	115	--	--	--	--	--	6	--	332
534894	WDEQ	49	73	-105.64419	44.22516	4,810	963	Wyodak	Upper Wyodak	--	1,000	8.0	29	15	247	--	--	--	--	--	6	--	703
535077	WDEQ	44	72	-105.49054	43.80840	4,836	900	Wyodak	Upper Wyodak	--	596	6.9	21	10	149	--	--	--	--	4	12	--	400
535083	WDEQ	46	72	-105.50124	43.91481	4,713	526	Anderson	Upper Wyodak	--	718	6.2	26	14	174	--	--	--	--	--	11	--	493
535173	WDEQ	47	73	-105.64664	44.07830	4,790	1,193	Wyodak	Upper Wyodak	--	724	6.4	26	12	168	--	--	--	--	--	9	--	509
535224	WDEQ	47	72	-105.54278	44.01139	4,853	1,010	Wyodak	Upper Wyodak	--	747	5.1	33	16	172	--	--	--	--	--	12	--	514
535232	WDEQ	47	73	-105.62667	44.07028	4,827	1,205	Wyodak	Upper Wyodak	--	694	6.3	26	13	170	--	--	--	--	--	15	--	470
535295	WDEQ	48	73	-105.67139	44.15417	4,808	358	Felix	Felix	--	805	12.4	21	6	220	--	--	--	--	--	8	--	550

Appendix A.

API	Source	Twn	Rng	Long	Lat	Elevation (feet)	Total Depth (feet)	Coal Bed	Coal Zone	pH	TDS (mg/L)	SAR	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	Sr (mg/L)	Ba (mg/L)	Fe (mg/L)	Si (mg/L)	SO_4 (mg/L)	Cl (mg/L)	F (mg/L)	Alkalinity (mg/L)
535462	WDEQ	47	73	-105.56985	44.05532	4,692	895	Wyodak	Upper Wyodak	--	1,036	6.0	40	20	250	--	--	--	--	--	10	--	716
535614	WDEQ	48	72	-105.50153	44.15045	4,762	782	Wyodak	Upper Wyodak	--	1,083	5.8	38	21	240	--	--	--	--	--	14	--	770
535625	WDEQ	45	75	-105.82564	43.87167	5,020	1,240	Big George	Wyodak Rider	--	1,397	8.6	46	14	340	--	--	--	--	--	17	--	980
535647	WDEQ	48	73	-105.66085	44.16111	4,827	1,070	Wyodak	Upper Wyodak	--	1,387	7.1	40	28	350	--	--	--	--	--	9	--	960
535740	WDEQ	55	75	-105.89573	44.72390	3,953	1,037	Anderson	Upper Wyodak	--	1,339	30.3	12	6	380	--	--	--	--	--	6	--	935
535815	WDEQ	53	75	-105.88643	44.57068	4,069	935	Werner	Cook	--	1,816	27.1	17	11	545	--	--	--	--	--	13	--	1,230
535820	WDEQ	53	75	-105.89565	44.57060	4,164	950	Anderson	Upper Wyodak	--	1,720	17.5	24	13	456	--	--	--	--	--	7	--	1,220
535909	WDEQ	51	74	-105.80965	44.37724	4,334	885	Anderson-Canyon	Upper Wyodak	--	803	65.0	0	4	246	--	--	--	--	2	0	--	551
535958	WDEQ	44	71	-105.38529	43.77261	4,874	650	Wyodak	Upper Wyodak	--	714	5.4	34	13	171	--	--	--	--	3	8	--	485
536285	WDEQ	41	72	-105.45033	43.54290	4,873	552	Wyodak	Upper Wyodak	--	431	8.0	14	6	109	--	--	--	--	--	8	--	294
536466	WDEQ	43	71	-105.42990	43.73608	4,874	742	Wyodak	Upper Wyodak	--	491	4.9	21	10	106	--	--	--	--	--	10	--	344
536585	WDEQ	47	73	-105.65153	44.07072	4,864	1,273	Wyodak	Upper Wyodak	--	412	8.1	16	4	105	--	--	--	--	--	10	--	277
536624	WDEQ	44	71	-105.44030	43.79780	4,920	740	Wyodak	Upper Wyodak	--	598	5.5	25	12	140	--	--	--	--	--	16	--	405
536630	WDEQ	44	71	-105.42580	43.80150	4,909	780	Wyodak	Upper Wyodak	--	627	7.2	24	9	160	--	--	--	--	--	14	--	420
536652	WDEQ	44	72	-105.46000	43.77640	4,890	843	Wyodak	Upper Wyodak	--	465	7.7	19	5	120	--	--	--	--	--	11	--	310
536708	WDEQ	44	73	-105.63485	43.78966	5,020	1,086	Wyodak	Upper Wyodak	--	613	6.5	31	5	146	--	--	--	--	3	8	--	420
536784	WDEQ	46	73	-105.68145	43.98948	4,956	1,018	Big George	Wyodak Rider	--	1,122	7.8	42	13	283	--	--	--	--	--	9	--	775
536861	WDEQ	48	72	-105.52681	44.15394	4,632	688	Wyodak	Upper Wyodak	--	436	7.4	14	7	108	--	--	--	--	--	9	--	298
536865	WDEQ	48	72	-105.53267	44.16808	4,669	710	Wyodak	Upper Wyodak	--	1,184	5.7	46	25	287	--	--	--	--	--	9	--	817

Appendix A.

API	Source	Twn	Rng	Long	Lat	Elevation (feet)	Total Depth (feet)	Coal Bed	Coal Zone	pH	TDS (mg/L)	SAR	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	Sr (mg/L)	Ba (mg/L)	Fe (mg/L)	Si (mg/L)	SO_4 (mg/L)	Cl (mg/L)	F (mg/L)	Alkalinity (mg/L)
536877	WDEQ	48	72	-105.51691	44.14662	4,603	631	Wyodak	Upper Wyodak	--	604	7.4	20	10	155	--	--	--	--	--	9	--	410
536896	WDEQ	50	73	-105.61853	44.32821	4,570	901	Wyodak	Upper Wyodak	--	843	9.6	21	12	225	--	--	--	--	--	7	--	578
537440	WDEQ	44	70	-105.30909	43.75734	4,799	300	Canyon	Lower Wyodak	--	945	6.4	38	15	231	--	--	--	--	8	23	--	630
537474	WDEQ	50	75	-105.89111	44.30613	4,669	1,883	Werner	Cook	--	2,046	11.2	46	24	550	--	--	--	--	--	16	--	1,410
537926	WDEQ	43	71	-105.40430	43.69961	4,833	610	Wyodak	Upper Wyodak	--	524	5.3	24	11	127	--	--	--	--	--	12	--	350
538057	WDEQ	46	71	-105.43337	43.92011	4,647	460	Wyodak	Upper Wyodak	--	813	6.9	31	12	200	--	--	--	--	3	12	--	555
538103	WDEQ	50	75	-105.88602	44.31004	4,635	1,797	Werner	Cook	--	1,833	17.0	26	16	510	--	--	--	--	6	15	--	1,260
538192	WDEQ	47	72	-105.51346	44.01511	4,889	1,794	Wyodak	Upper Wyodak	--	367	15.4	8	2	100	--	--	--	--	--	5	--	252
538268	WDEQ	48	74	-105.71053	44.17039	4,953	1,507	Wyodak	Upper Wyodak	--	673	10.6	19	7	186	--	--	--	--	--	16	--	445
538291	WDEQ	55	75	-105.90068	44.74614	3,976	688	Canyon Rider	Lower Wyodak	--	1,583	21.7	20	10	453	--	--	--	--	--	0	--	1,100
538739	WDEQ	56	74	-105.81317	44.81523	4,076	935	Canyon	Lower Wyodak	--	1,310	27.3	14	7	400	--	--	--	--	--	8	--	881
538864	WDEQ	44	71	-105.38522	43.79388	4,979	665	Wyodak	Upper Wyodak	--	532	6.9	22	8	140	--	--	--	--	--	12	--	350
538892	WDEQ	44	71	-105.38480	43.82310	4,854	565	Wyodak	Upper Wyodak	--	989	6.8	42	12	240	--	--	--	--	373	12	--	310
538899	WDEQ	44	71	-105.39431	43.81588	4,887	725	Wyodak	Upper Wyodak	--	980	6.9	42	13	250	--	--	--	--	345	0	--	330
539104	WDEQ	44	71	-105.40560	43.81650	4,924	750	Wyodak	Upper Wyodak	--	528	6.4	24	7	130	--	--	--	--	--	12	--	355
539390	WDEQ	45	72	-105.46878	43.83017	4,796	780	Wyodak	Upper Wyodak	--	494	8.6	15	7	131	--	--	--	--	--	9	--	332
539651	WDEQ	48	72	-105.55220	44.16161	4,701	826	Wyodak	Upper Wyodak	--	689	6.9	21	13	169	--	--	--	--	--	9	--	477
539658	WDEQ	47	73	-105.68832	44.08147	4,833	1,288	Wyodak	Upper Wyodak	--	545	8.1	16	8	136	--	--	--	--	--	9	--	376
539672	WDEQ	47	73	-105.68141	44.04123	4,883	1,311	Wyodak	Upper Wyodak	--	752	6.4	29	12	180	--	--	--	--	--	11	--	520

Appendix A.

API	Source	Twn	Rng	Long	Lat	Elevation (feet)	Total Depth (feet)	Coal Bed	Coal Zone	pH	TDS (mg/L)	SAR	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	Sr (mg/L)	Ba (mg/L)	Fe (mg/L)	Si (mg/L)	SO_4 (mg/L)	Cl (mg/L)	F (mg/L)	Alkalinity (mg/L)
539748	WDEQ	44	71	-105.33955	43.75749	4,772	357	Canyon	Lower Wyodak	--	872	5.6	40	15	209	--	--	--	--	5	13	--	590
539855	WDEQ	45	72	-105.46278	43.87056	4,759	696	Wyodak	Upper Wyodak	--	616	7.4	--	--	--	--	--	--	--	--	--	--	--
539865	WDEQ	44	71	-105.43986	43.74009	4,925	830	Wyodak	Upper Wyodak	--	577	5.4	24	11	131	--	--	--	--	--	11	--	400
539982	WDEQ	45	72	-105.54500	43.84806	4,963	1,200	Wyodak	Upper Wyodak	--	751	8.5	21	11	190	--	--	--	--	9	10	--	510
539987	WDEQ	45	72	-105.54417	43.87722	4,899	884	Wyodak	Upper Wyodak	--	669	7.5	23	10	170	--	--	--	--	--	16	--	450
540060	WDEQ	48	72	-105.56368	44.16820	4,746	901	Wyodak	Upper Wyodak	--	931	5.0	37	22	209	--	--	--	--	--	9	--	654
540176	WDEQ	55	76	-105.99694	44.75566	3,943	1,051	Cook	Cook	--	2,203	29.7	19	12	660	--	--	--	--	--	12	--	1,500
540329	WDEQ	43	71	-105.39983	43.65957	4,927	640	Wyodak	Upper Wyodak	--	532	5.9	22	10	130	--	--	--	--	--	15	--	355
540373	WDEQ	48	73	-105.68694	44.13966	4,919	508	Felix	Felix	--	841	13.3	22	5	230	--	--	--	--	--	14	--	570
540414	WDEQ	47	74	-105.71697	44.04469	4,978	1,432	Wyodak	Upper Wyodak	--	386	17.4	8	2	113	--	--	--	--	--	8	--	255
540498	WDEQ	48	73	-105.58949	44.14026	4,845	1,002	Wyodak	Upper Wyodak	--	992	4.7	43	24	223	--	--	--	--	--	9	--	693
540748	WDEQ	45	72	-105.44722	43.87417	4,735	600	Anderson	Upper Wyodak	--	650	7.3	24	9	162	--	--	--	--	--	15	--	440
540780	WDEQ	48	73	-105.65083	44.15806	4,830	1,036	Wyodak	Upper Wyodak	--	1,213	7.2	34	25	310	--	--	--	--	5	11	--	828
540831	WDEQ	44	72	-105.49000	43.81410	4,894	980	Wyodak	Upper Wyodak	--	667	5.5	27	13	154	--	--	--	--	--	8	--	465
540947	WDEQ	44	72	-105.56110	43.81110	5,041	1,158	Wyodak	Upper Wyodak	--	782	6.7	29	14	200	--	--	--	--	--	9	--	530
540966	WDEQ	55	74	-105.7725	44.765	4,102	731	Cook	Cook	--	1,544	22.3	19	10	454	--	--	--	--	--	11	--	1,050
541019	WDEQ	48	73	-105.68167	44.12528	4,869	1,259	Wyodak	Upper Wyodak	--	814	11.1	23	7	220	--	--	--	--	--	5	--	559
541095	WDEQ	41	71	-105.42554	43.52822	4,950	631	Wyodak	Upper Wyodak	--	510	10.5	16	4	136	--	--	--	--	--	6	--	348
541155	WDEQ	44	72	-105.51050	43.81180	4,874	1,003	Wyodak	Upper Wyodak	--	669	5.7	29	14	170	--	--	--	--	--	11	--	445

Appendix A.

API	Source	Twn	Rng	Long	Lat	Elevation (feet)	Total Depth (feet)	Coal Bed	Coal Zone	pH	TDS (mg/L)	SAR	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	Sr (mg/L)	Ba (mg/L)	Fe (mg/L)	Si (mg/L)	SO_4 (mg/L)	Cl (mg/L)	F (mg/L)	Alkalinity (mg/L)
541259	WDEQ	55	74	-105.7768	44.7654	4,091	565	Canyon	Lower Wyodak	--	1,586	21.1	19	12	469	--	--	--	--	--	6	--	1,080
541421	WDEQ	50	72	-105.53721	44.28522	4,643	558	Anderson	Upper Wyodak	--	1,712	3.7	91	52	380	--	--	--	--	181	8	--	1,000
541481	WDEQ	49	73	-105.62889	44.18833	4,793	1,005	Wyodak	Upper Wyodak	--	1,225	6.3	39	28	310	--	--	--	--	--	8	--	840
541691	WDEQ	53	73	-105.66417	44.59838	4,183	649	Cook	Cook	--	1,363	8.9	41	18	360	--	--	--	--	--	8	--	936
541941	WDEQ	48	74	-105.70180	44.14190	4,954	1,374	Wyodak	Upper Wyodak	--	1,502	5.4	56	36	354	--	--	--	--	--	16	--	1,040
541973	WDEQ	48	74	-105.70250	44.14960	4,901	1,410	Wyodak	Upper Wyodak	--	1,613	5.3	62	41	396	--	--	--	--	--	14	--	1,100
542070	WDEQ	48	74	-105.75899	44.09488	4,904	1,405	Wyodak	Upper Wyodak	--	1,105	11.4	36	8	322	--	--	--	--	--	8	--	731
542147	WDEQ	45	74	-105.70112	43.89108	4,946	876	Big George	Wyodak Rider	--	1,035	9.2	34	9	257	--	--	--	--	1	10	--	724
542177	WDEQ	46	74	-105.78283	43.93043	5,041	1,237	Big George	Wyodak Rider	--	1,026	10.6	33	8	280	--	--	--	--	--	10	--	695
542206	WDEQ	43	73	-105.6574	43.6544	5,181	950	Big George	Wyodak Rider	--	1,169	6.4	54	15	290	--	--	--	--	--	15	--	795
542211	WDEQ	42	73	-105.5817	43.6149	5,030	900	Canyon	Lower Wyodak	--	542	13.0	14	4	154	--	--	--	--	--	7	--	363
542421	WDEQ	49	73	-105.60333	44.19306	4,880	955	Wyodak	Upper Wyodak	--	1,185	5.5	47	27	290	--	--	--	--	--	11	--	810
542608	WDEQ	49	72	-105.56643	44.25454	4,701	706	Anderson	Upper Wyodak	--	1,043	7.0	27	21	249	--	--	--	--	--	9	--	737
542621	WDEQ	50	73	-105.62888	44.33864	4,448	660	Anderson	Upper Wyodak	--	2,082	2.2	160	67	340	--	--	--	--	986	6	--	523
542668	WDEQ	49	72	-105.51665	44.20472	4,743	734	Anderson	Upper Wyodak	--	718	6.8	27	13	190	--	--	--	--	--	13	--	475
542857	WDEQ	48	73	-105.68778	44.08861	4,838	1,300	Wyodak	Upper Wyodak	--	835	5.5	32	18	196	--	--	--	--	--	11	--	578
542962	WDEQ	53	73	-105.66434	44.59851	4,182	500	Canyon	Lower Wyodak	--	869	15.9	17	6	245	--	--	--	--	--	8	--	593
543063	WDEQ	54	76	-105.9519	44.63111	3,859	833	Canyon	Lower Wyodak	--	1,465	22.2	19	8	409	--	--	--	--	--	9	--	1,020
543270	WDEQ	49	73	-105.63389	44.22861	4,774	910	Wyodak	Upper Wyodak	--	913	8.5	26	12	224	--	--	--	--	6	7	--	638

Appendix A.

API	Source	Twn	Rng	Long	Lat	Elevation (feet)	Total Depth (feet)	Coal Bed	Coal Zone	pH	TDS (mg/L)	SAR	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	Sr (mg/L)	Ba (mg/L)	Fe (mg/L)	Si (mg/L)	SO_4 (mg/L)	Cl (mg/L)	F (mg/L)	Alkalinity (mg/L)
543448	WDEQ	54	74	-105.74064	44.6596	4,262	876	Canyon	Lower Wyodak	--	1,420	18.5	0	22	384	--	--	--	--	--	14	--	1,000
543568	WDEQ	42	73	-105.60176	43.60699	5,114	890	Anderson	Upper Wyodak	--	362	14.2	9	2	100	--	--	--	--	--	7	--	244
543627	WDEQ	43	73	-105.58056	43.65083	5,091	1,041	Canyon	Lower Wyodak	--	663	12.2	18	5	184	--	--	--	--	--	7	--	449
543663	WDEQ	55	75	-105.932	44.7307	4,014	1,068	Wall	Wall	--	2,101	31.7	16	11	620	--	--	--	--	--	14	--	1,440
543722	WDEQ	51	74	-105.69696	44.39672	4,591	1,028	Canyon	Lower Wyodak	--	844	11.2	22	8	225	--	--	--	--	24	8	--	557
543803	WDEQ	51	74	-105.7276	44.3685	4,520	809	Anderson	Upper Wyodak	--	1,069	10.5	30	10	280	--	--	--	--	--	14	--	735
543868	WDEQ	45	72	-105.46861	43.83750	4,778	760	Wyodak	Upper Wyodak	--	555	7.2	18	10	143	--	--	--	--	--	8	--	376
543879	WDEQ	45	72	-105.49361	43.87665	4,847	710	Anderson	Upper Wyodak	--	628	5.1	28	14	150	--	--	--	--	--	11	--	425
543895	WDEQ	50	73	-105.57793	44.29939	4,675	733	Anderson	Upper Wyodak	--	1,282	7.1	31	29	321	--	--	--	--	--	8	--	893
543897	WDEQ	50	73	-105.58861	44.29926	4,748	844	Anderson	Upper Wyodak	--	1,329	8.2	29	27	346	--	--	--	--	--	7	--	920
544380	WDEQ	56	74	-105.80399	44.81578	4,054	725	Cook-Lower Cook-Wall	Multiple	--	1,647	30.3	13	9	484	--	--	--	--	--	11	--	1,130
544498	WDEQ	51	74	-105.7464	44.4045	4,537	845	Anderson	Upper Wyodak	--	1,326	11.3	34	12	350	--	--	--	--	--	10	--	920
544924	WDEQ	46	72	-105.51200	43.95181	4,730	735	Wyodak	Upper Wyodak	--	1,029	6.0	28	15	180	--	--	--	--	--	10	--	796
544932	WDEQ	46	72	-105.53340	43.95149	4,712	785	Wyodak	Upper Wyodak	--	936	5.4	37	21	220	--	--	--	--	--	10	--	648
545162	WDEQ	46	73	-105.63601	43.96392	4,859	1,309	Wyodak	Upper Wyodak	--	411	15.0	9	3	120	--	--	--	--	--	9	--	270
545298	WDEQ	50	73	-105.68014	44.26136	4,691	1,010	Anderson	Upper Wyodak	--	1,055	5.5	35	16	193	--	--	--	--	--	7	--	804
545469	WDEQ	55	74	-105.7527	44.72847	4,152	976	Wall	Wall	--	1,569	15.3	23	17	449	--	--	--	--	--	10	--	1,070
545513	WDEQ	48	74	-105.69719	44.16053	4,866	1,286	Wyodak	Upper Wyodak	--	1,251	7.1	42	24	330	--	--	--	--	--	8	--	847
545626	WDEQ	44	74	-105.69278	43.74583	4,982	1,093	Wyodak	Upper Wyodak	--	732	10.1	28	4	200	--	--	--	--	--	10	--	490

Appendix A.

API	Source	Twn	Rng	Long	Lat	Elevation (feet)	Total Depth (feet)	Coal Bed	Coal Zone	pH	TDS (mg/L)	SAR	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	Sr (mg/L)	Ba (mg/L)	Fe (mg/L)	Si (mg/L)	SO_4 (mg/L)	Cl (mg/L)	F (mg/L)	Alkalinity (mg/L)
545736	WDEQ	47	73	-105.68290	44.04850	4,878	1,321	Wyodak	Upper Wyodak	--	673	7.1	25	10	170	--	--	--	--	--	8	--	460
545748	WDEQ	47	73	-105.66290	44.08170	4,802	1,237	Wyodak	Upper Wyodak	--	945	5.3	40	18	210	--	--	--	--	--	15	--	662
545978	WDEQ	44	72	-105.47030	43.79060	4,849	825	Wyodak	Upper Wyodak	--	545	5.8	26	8	130	--	--	--	--	--	11	--	370
546030	WDEQ	44	71	-105.43550	43.74360	4,921	820	Wyodak	Upper Wyodak	--	586	5.8	24	11	140	--	--	--	--	--	16	--	395
546171	WDEQ	45	73	-105.65667	43.86167	4,872	1,103	Big George-Canyon	Multiple	--	1,020	7.8	41	10	256	--	--	--	--	3	8	--	702
546320	WDEQ	43	74	-105.68778	43.69781	5,045	953	Big George	Wyodak Rider	--	973	6.9	38	14	240	--	--	--	--	37	12	--	632
546692	WDEQ	50	75	-105.88668	44.31105	4,636	1,413	Big George	Wyodak Rider	--	1,270	23.2	16	7	367	--	--	--	--	2	14	--	864
547353	WDEQ	50	74	-105.7914	44.34201	4,373	1,574	Wall	Wall	--	586	9.6	20	5	156	--	--	--	--	--	15	--	390
547356	WDEQ	43	74	-105.70722	43.71972	5,139	1,200	Big George	Wyodak Rider	--	774	6.8	37	7	190	--	--	--	--	9	9	--	522
547480	WDEQ	55	74	-105.80501	44.72077	4,127	1,000	Wall	Wall	--	1,567	19.2	21	11	431	--	--	--	--	--	14	--	1,090
547516	WDEQ	44	72	-105.51550	43.76490	4,941	984	Wyodak	Upper Wyodak	--	812	4.7	43	17	190	--	--	--	--	--	12	--	550
547556	WDEQ	44	72	-105.52560	43.81530	4,921	853	Wyodak	Upper Wyodak	--	815	6.2	33	16	210	--	--	--	--	--	11	--	545
548006	WDEQ	53	76	-105.9511	44.541	3,929	793	Anderson	Upper Wyodak	--	1,106	21.0	15	7	320	--	--	--	--	--	14	--	750
548076	WDEQ	44	71	-105.37000	43.78310	4,828	507	Wyodak	Upper Wyodak	--	753	5.1	41	13	183	--	--	--	--	--	11	--	505
548155	WDEQ	56	74	-105.80395	44.80797	4,134	803	Wall	Wall	--	1,430	32.4	14	5	413	--	--	--	--	--	14	--	984
548341	WDEQ	45	75	-105.86083	43.88639	4,836	1,650	Big George	Wyodak Rider	--	2,637	5.7	120	37	590	--	--	--	--	--	0	--	1,890
548470	WDEQ	50	75	-105.8865	44.29661	4,706	1,390	Big George	Wyodak Rider	--	1,647	17.0	30	11	468	--	--	--	--	--	8	--	1,130
548980	WDEQ	43	73	-105.65239	43.66529	5,167	990	Big George	Wyodak Rider	--	894	7.9	36	9	230	--	--	--	--	2	12	--	605
549215	WDEQ	44	75	-105.85802	43.75668	5,280	1,510	Big George	Wyodak Rider	--	1,672	8.4	53	22	430	--	--	--	--	--	7	--	1,160

Appendix A.

API	Source	Twn	Rng	Long	Lat	Elevation (feet)	Total Depth (feet)	Coal Bed	Coal Zone	pH	TDS (mg/L)	SAR	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	Sr (mg/L)	Ba (mg/L)	Fe (mg/L)	Si (mg/L)	SO_4 (mg/L)	Cl (mg/L)	F (mg/L)	Alkalinity (mg/L)
549492	WDEQ	42	73	-105.6828	43.6432	5,149	982	Big George	Wyodak Rider	--	890	6.3	40	10	204	--	--	--	--	--	9	--	627
549560	WDEQ	42	71	-105.36091	43.64472	4,865	501	Wyodak	Upper Wyodak	--	659	4.8	29	14	142	--	--	--	--	3	10	--	461
549883	WDEQ	48	74	-105.70880	44.10346	4,908	1,464	Wyodak	Upper Wyodak	--	787	5.4	27	20	186	--	--	--	--	--	10	--	544
549937	WDEQ	43	71	-105.39005	43.66686	4,830	519	Wyodak	Upper Wyodak	--	473	5.5	22	8	110	--	--	--	--	--	11	--	322
549938	WDEQ	43	71	-105.38469	43.67806	4,814	564	Wyodak	Upper Wyodak	--	476	5.6	20	8	106	--	--	--	--	2	12	--	328
549953	WDEQ	42	73	-105.57642	43.61102	5,093	927	Canyon	Lower Wyodak	--	537	12.1	15	4	150	--	--	--	--	--	8	--	360
549982	WDEQ	45	74	-105.72198	43.8433	4,955	971	Big George	Wyodak Rider	--	1,284	7.6	49	13	305	--	--	--	--	4	8	--	905
550088	WDEQ	45	74	-105.70197	43.88758	4,978	933	Big George	Wyodak Rider	--	1,091	10.2	29	11	276	--	--	--	--	1	8	--	766
550135	WDEQ	45	72	-105.52972	43.85944	4,916	1,150	Wyodak	Upper Wyodak	--	829	6.5	32	13	200	--	--	--	--	--	14	--	570
550448	WDEQ	45	75	-105.86213	43.89739	4,820	1,150	Big George	Wyodak Rider	--	2,693	6.8	112	37	673	--	--	--	--	3	8	--	1,860
550536	WDEQ	50	75	-105.87142	44.31474	4,547	1,961	Wall	Wall	--	1,900	13.0	41	18	525	--	--	--	--	2	14	--	1,300
550777	WDEQ	42	71	-105.44071	43.56517	5,016	763	Wyodak	Upper Wyodak	--	451	6.5	17	7	106	--	--	--	--	--	8	--	313
550828	WDEQ	45	73	-105.60694	43.90611	4,783	1,245	Canyon	Lower Wyodak	--	675	6.1	22	15	164	--	--	--	--	--	8	--	466
550857	WDEQ	46	75	-105.87697	43.97739	4,729	1,276	Big George	Wyodak Rider	--	1,560	10.2	43	16	404	--	--	--	--	--	7	--	1,090
551100	WDEQ	43	75	-105.83322	43.73107	5,236	1,354	Big George	Wyodak Rider	--	1,490	6.2	64	24	367	--	--	--	--	8	7	--	1,020
551140	WDEQ	49	74	-105.73013	44.19574	4,821	1,051	Wyodak	Upper Wyodak	--	918	12.1	21	8	237	--	--	--	--	--	7	--	645
551276	WDEQ	45	74	-105.80693	43.86103	5,058	1,283	Big George	Wyodak Rider	--	1,495	8.4	52	17	387	--	--	--	--	--	9	--	1,030
551641	WDEQ	42	74	-105.72362	43.62164	5,293	1,046	Big George	Wyodak Rider	--	889	6.5	45	9	222	--	--	--	--	2	10	--	601
551739	WDEQ	41	72	-105.52098	43.53466	4,898	737	Wyodak	Upper Wyodak	--	379	11.3	9	4	101	--	--	--	--	--	7	--	258

Appendix A.

API	Source	Twn	Rng	Long	Lat	Elevation (feet)	Total Depth (feet)	Coal Bed	Coal Zone	pH	TDS (mg/L)	SAR	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	Sr (mg/L)	Ba (mg/L)	Fe (mg/L)	Si (mg/L)	SO_4 (mg/L)	Cl (mg/L)	F (mg/L)	Alkalinity (mg/L)
552087	WDEQ	44	74	-105.77281	43.75964	5,068	1,074	Big George	Wyodak Rider	--	1,055	7.8	40	10	254	--	--	--	--	--	7	--	744
552100	WDEQ	56	75	-105.91206	44.86358	3,709	691	Cook-Wall	Multiple	--	1,961	56.6	9	4	506	--	--	--	--	--	12	--	1,430
552371	WDEQ	42	74	-105.7575	43.57417	5,147	842	Big George	Wyodak Rider	--	700	6.7	32	7	168	--	--	--	--	--	6	--	487
553615	WDEQ	42	74	-105.77839	43.61041	5,330	1,160	Big George	Wyodak Rider	--	912	6.1	47	9	218	--	--	--	--	5	8	--	625
555244	WDEQ	53	75	-105.92748	44.60623	3,980	1,175	Anderson-Werner	Multiple	--	2,436	24.2	25	16	712	--	--	--	--	34	29	--	1,620
1921093	WDEQ	50	78	-106.18547	44.25831	4,018	1,603	Big George	Wyodak Rider	--	2,761	59.3	14	6	812	--	--	--	--	10	59	--	1,860
1921143	WDEQ	47	77	-106.06075	44.00779	4,359	1,345	Big George	Wyodak Rider	--	2,464	18.3	31	20	673	--	--	--	--	--	10	--	1,730
1921146	WDEQ	47	77	-106.06018	44.00327	4,315	1,365	Big George	Wyodak Rider	--	2,697	20.7	28	20	722	--	--	--	--	--	17	--	1,910
1921764	WDEQ	47	77	-106.10766	44.01905	4,230	1,325	Big George	Wyodak Rider	--	3,566	22.0	34	28	1010	--	--	--	--	1	23	--	2,470
1921802	WDEQ	42	77	-106.1261	43.6053	5,093	1,178	Big George	Wyodak Rider	--	1,817	9.5	34	33	480	--	--	--	--	--	10	--	1,260
1922069	WDEQ	52	81	-106.54492	44.47204	4,283	750	Roland	Roland	--	972	35.8	7	4	279	--	--	--	--	--	17	--	665
1922125	WDEQ	43	76	-106.03641	43.69462	4,688	1,410	Big George	Wyodak Rider	--	1,398	5.2	37	37	293	--	--	--	--	--	11	--	1,020
1922364	WDEQ	52	81	-106.54539	44.47219	4,283	1,450	Anderson	Upper Wyodak	--	1,381	39.4	9	5	390	--	--	--	--	--	14	--	963
1922375	WDEQ	53	77	-106.10266	44.542	3,763	1,543	Wall	Wall	--	1,604	47.3	2	9	457	--	--	--	--	--	26	--	1,110
1922413	WDEQ	51	77	-106.14340	44.38606	3,821	1,168	Anderson	Upper Wyodak	--	618	17.1	12	4	182	--	--	--	--	1	8	--	411
1922441	WDEQ	49	78	-106.27028	44.18833	4,506	2,042	Big George	Wyodak Rider	--	2,910	27.9	31	13	838	--	--	--	--	--	38	--	1,990
1922819	WDEQ	48	77	-106.13015	44.16363	4,102	1,332	Big George	Wyodak Rider	--	3,466	9.9	119	28	939	--	--	--	--	481	29	--	1,870
1922876	WDEQ	44	77	-106.12393	43.79478	4,570	1,453	Big George	Wyodak Rider	--	4,040	15.0	34	56	1090	--	--	--	--	--	10	--	2,850
1923367	WDEQ	42	77	-106.08586	43.60598	4,886	1,248	Big George	Wyodak Rider	--	911	6.6	23	21	217	--	--	--	--	--	7	--	643

Appendix A.

API	Source	Twn	Rng	Long	Lat	Elevation (feet)	Total Depth (feet)	Coal Bed	Coal Zone	pH	TDS (mg/L)	SAR	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	Sr (mg/L)	Ba (mg/L)	Fe (mg/L)	Si (mg/L)	SO_4 (mg/L)	Cl (mg/L)	F (mg/L)	Alkalinity (mg/L)
1923406	WDEQ	42	77	-106.12007	43.6019	5,109	1,318	Big George	Wyodak Rider	--	1,463	7.1	29	34	345	--	--	--	--	18	7	--	1,030
1923419	WDEQ	51	77	-106.16578	44.37459	3,881	1,731	Wall	Wall	--	2,664	74.3	2	10	788	--	--	--	--	35	49	--	1,780
1924063	WDEQ	48	77	-106.1544	44.12442	4,107	1,280	Big George	Wyodak Rider	--	2,978	16.3	43	24	773	--	--	--	--	--	28	--	2,110
1924243	WDEQ	51	77	-106.14527	44.34423	3,897	1,270	Smith Rider-Lower Smith	Wyodak Rider	--	3,317	37.6	16	18	986	--	--	--	--	15	32	--	2,250
1925324	WDEQ	49	77	-106.05903	44.17472	4,417	1,377	Big George	Wyodak Rider	--	3,191	29.3	16	16	711	--	--	--	--	780	18	--	1,650
1926216	WDEQ	43	77	-106.11977	43.72497	4,558	1,525	Big George	Wyodak Rider	--	1,517	7.1	34	35	371	--	--	--	--	--	7	--	1,070
3320926	WDEQ	55	77	-106.06501	44.70065	3,980	727	Anderson	Upper Wyodak	--	2,044	29.4	21	9	605	--	--	--	--	--	9	--	1,400
3322681	WDEQ	57	83	-106.85722	44.90681	3,584	944	Dietz 3	Upper Wyodak	--	1,675	79.2	6	3	497	--	--	--	--	8	21	--	1,140
3323124	WDEQ	58	79	-106.42334	44.96866	3,728	395	Anderson	Upper Wyodak	--	1,755	70.8	7	3	485	--	--	--	--	--	20	--	1,240
3323132	WDEQ	58	79	-106.42387	44.97635	3,727	347	Anderson	Upper Wyodak	--	1,841	107.9	6	2	575	--	--	--	--	--	28	--	1,230
3323184	WDEQ	57	83	-106.91257	44.91738	3,724	346	Smith-Anderson	Multiple	--	1,382	136.1	0	3	386	--	--	--	--	5	28	--	960
3325003	WDEQ	57	82	-106.79631	44.93564	3,653	1,065	Dietz 3	Upper Wyodak	--	2,072	91.0	9	2	642	--	--	--	--	20	239	--	1,160
3325353	WDEQ	58	79	-106.43361	44.97629	3,745	952	Cook	Cook	--	2,075	62.7	16	0	575	--	--	--	--	--	44	--	1,440

www.wsgs.uwyo.edu

Geology — Interpreting the past – providing for the future

ISBN 978-1-884589-59-1